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Chiussi et al.

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(54) GUARANTEEING DATA TRANSFER DELAYS IN DATA PACKET NETWORKS USING EARLIEST DEADLINE FIRST PACKET SCHEDULERS

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(22) Filed: **May 14, 1999**

Related U.S. Application Data

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(51) **Int. Cl.**^{7} **H04L 12/56**

(52) **U.S. Cl.** **370/230.1**; 370/235.1

(58) **Field of Search** 370/389, 395.1, 370/395.4, 412, 413, 417, 235.1, 230.1

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(57) **ABSTRACT**

A system is disclosed that services a plurality of queues associated with respective data connections in a packet communication network such that the system guarantees data transfer delays between the data source and the destination of each data connection. This is achieved in two stages. The first stage shapes the traffic of each connection such that it conforms to a specified envelope. The second stage associates timestamps with the packets released by the first stage and chooses for transmission from among them the one with the smallest timestamp. Both stages are associated with a discrete set of delay classes. The first stage employs one shaping structure per delay class. Each shaping structure in turn supports a discrete set of rates and employs a FIFO of connections per supported rate. A connection may move between FIFOs corresponding to different rates as its rate requirement changes. The second stage associates with each packet exiting the first stage a timestamp given by the exit time from the first stage and the delay class to which the connection belongs. A queue of packets is maintained per delay class, and the scheduler selects for transmission from among the packets at the head of the queues the one with the smallest timestamp.

15 Claims, 15 Drawing Sheets

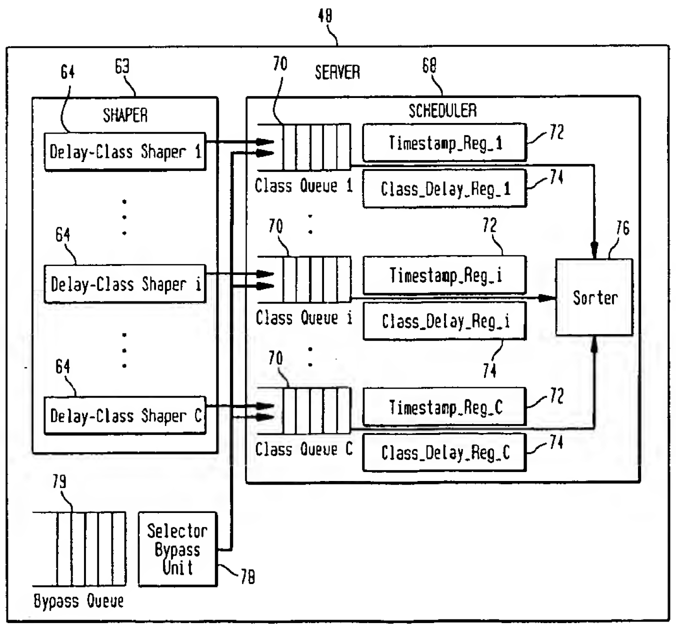


FIG. 1
(PRIOR ART)

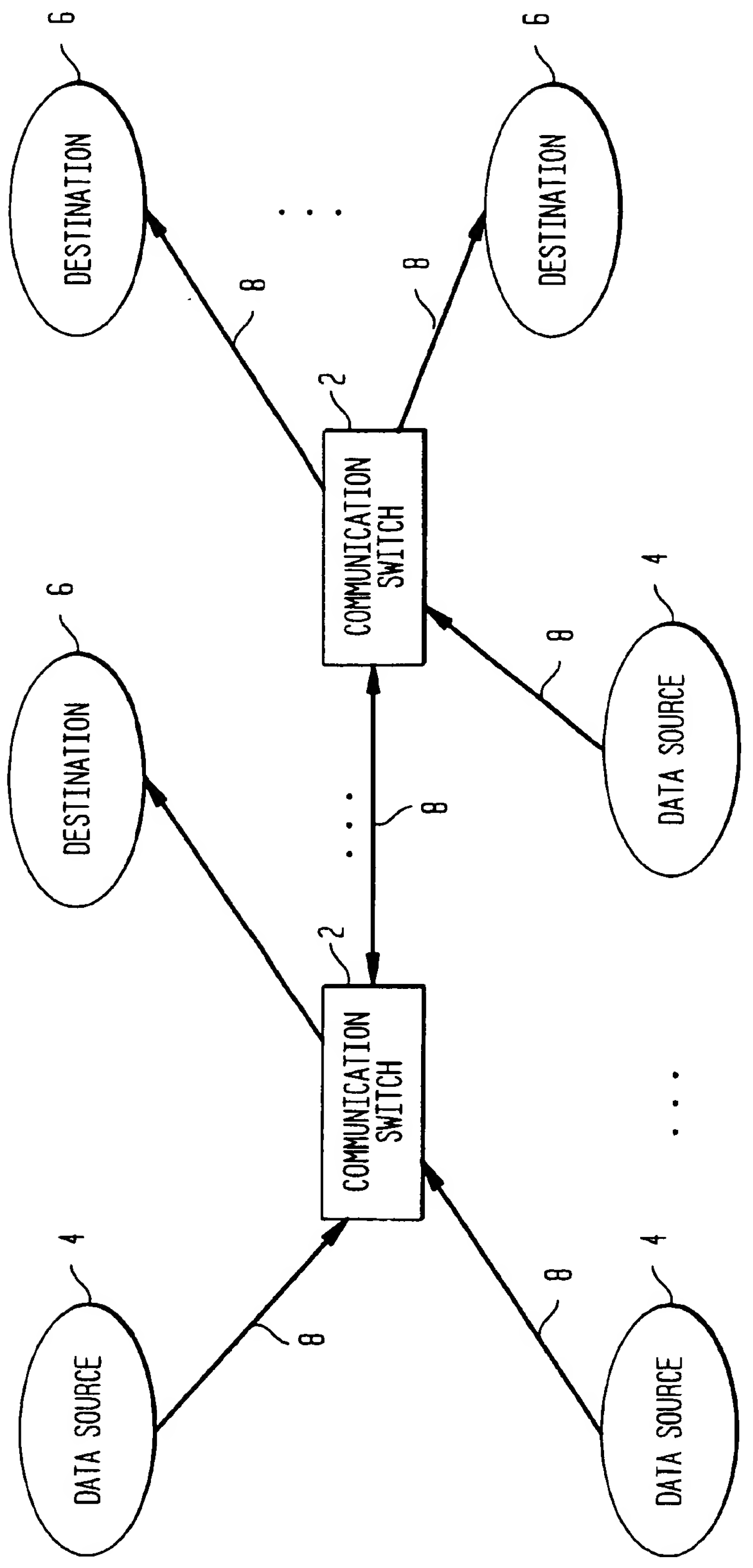


FIG. 2
(PRIOR ART)

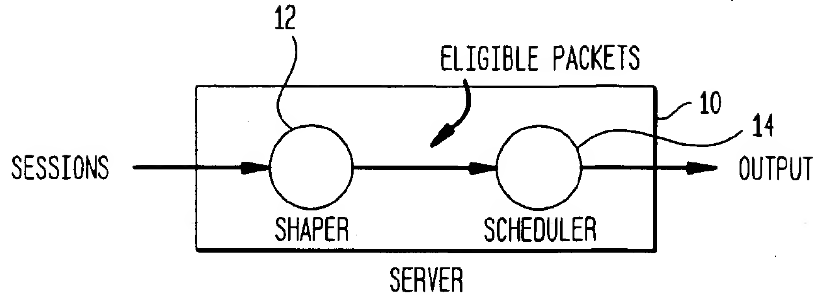


FIG. 3
(PRIOR ART)

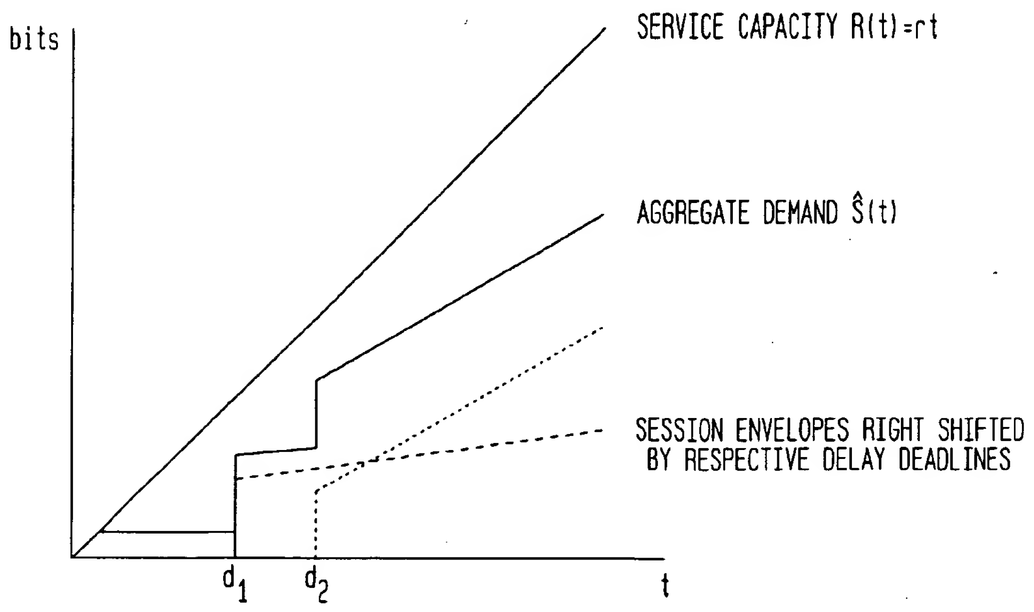


FIG. 4

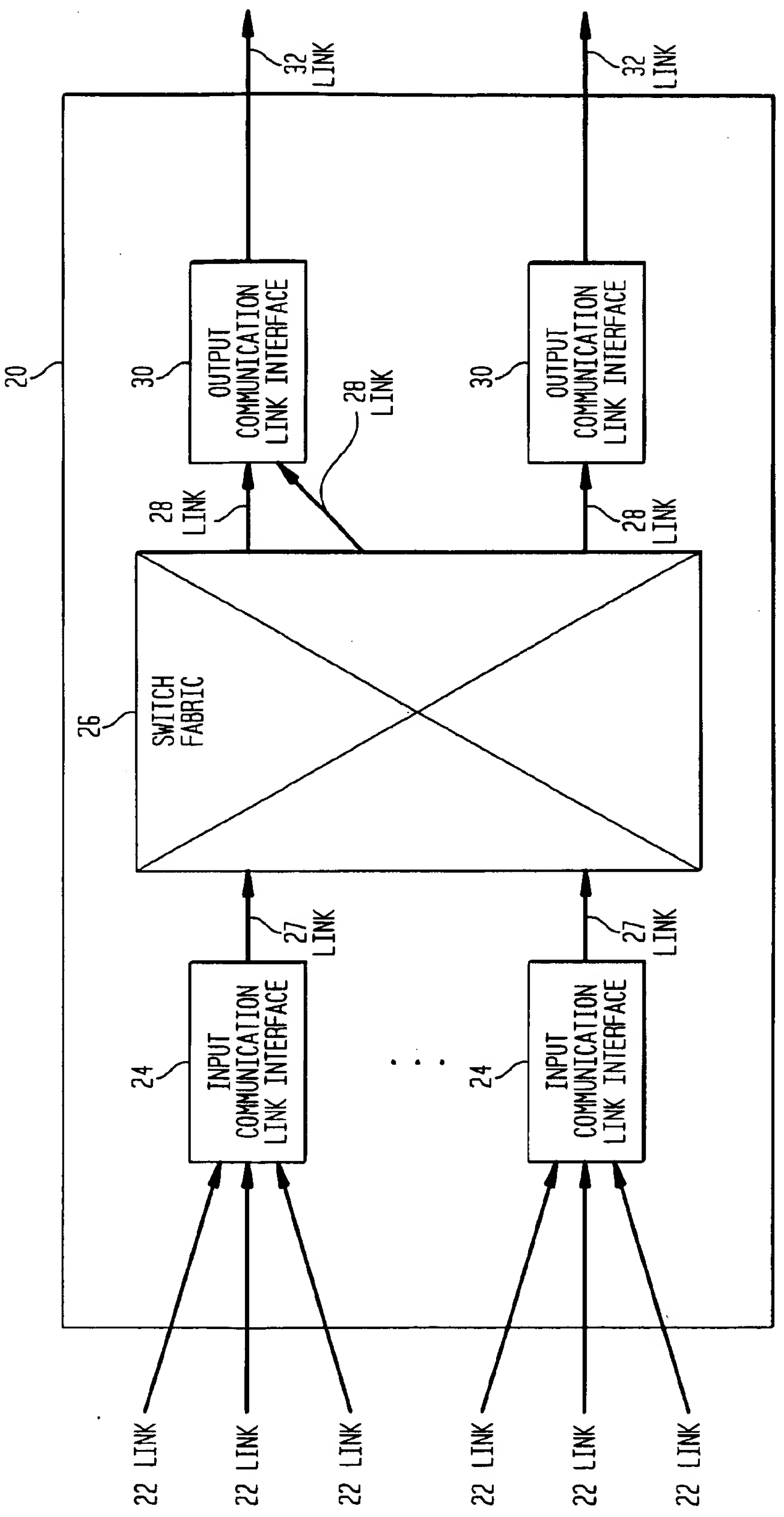

20
32 LINK
32 LINK
30
OUTPUT COMMUNICATION LINK INTERFACE
30
OUTPUT COMMUNICATION LINK INTERFACE
28 LINK
28 LINK
28 LINK
26
SWITCH FABRIC
27 LINK
27 LINK
24
INPUT COMMUNICATION LINK INTERFACE
24
INPUT COMMUNICATION LINK INTERFACE
22 LINK
22 LINK
22 LINK
22 LINK
22 LINK
22 LINK

FIG. 5

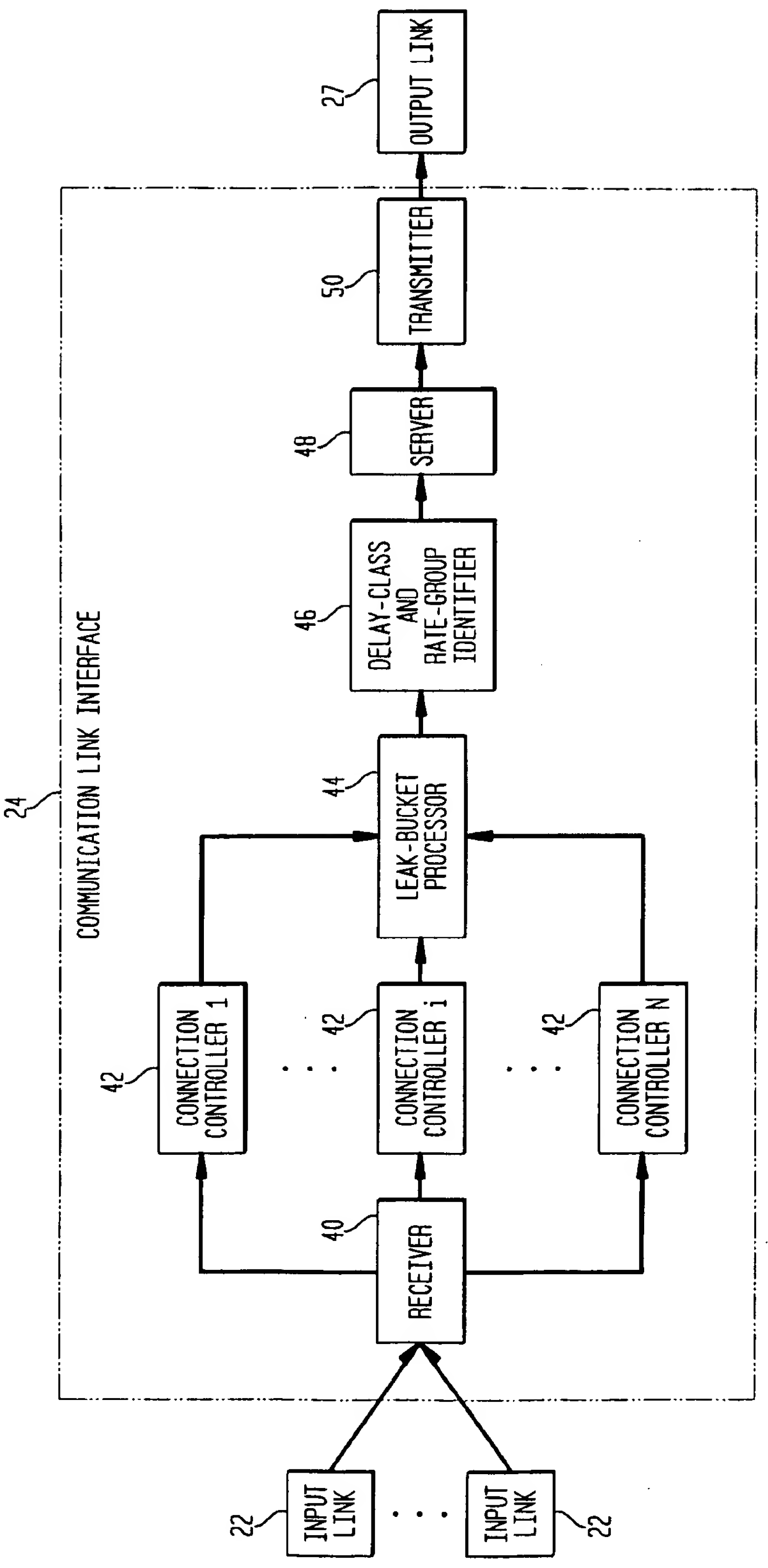

24
COMMUNICATION LINK INTERFACE
22
INPUT LINK
22
INPUT LINK
40
RECEIVER
42
CONNECTION CONTROLLER 1
42
CONNECTION CONTROLLER i
42
CONNECTION CONTROLLER N
44
LEAK-BUCKET PROCESSOR
46
DELAY-CLASS AND RATE-GROUP IDENTIFIER
48
SERVER
50
TRANSMITTER
27
OUTPUT LINK

FIG. 6

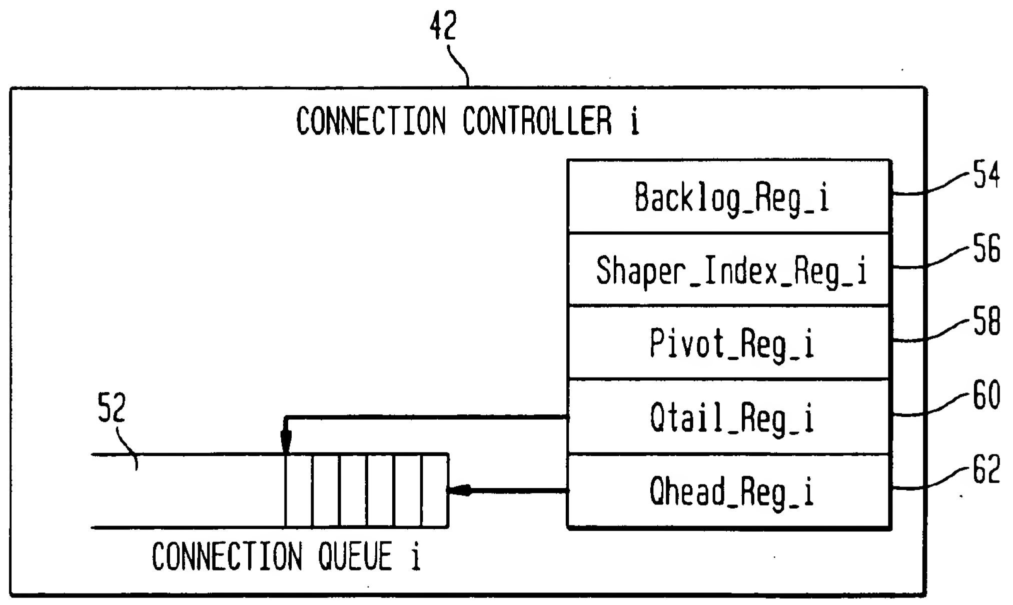

42
CONNECTION CONTROLLER i
Backlog_Reg_i
Shaper_Index_Reg_i
Pivot_Reg_i
Qtail_Reg_i
Qhead_Reg_i
54
56
58
60
62
52
CONNECTION QUEUE i

FIG. 7

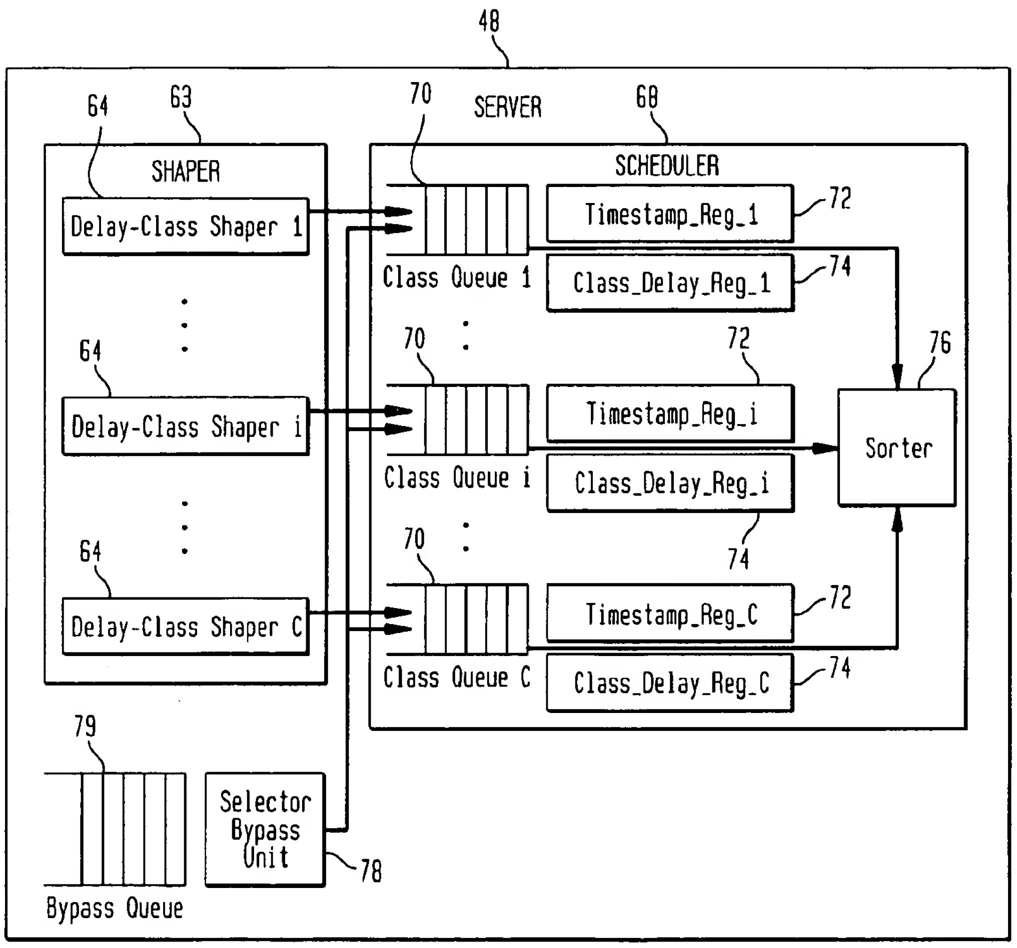

48
SERVER
64
63
SHAPER
Delay-Class Shaper 1
64
Delay-Class Shaper i
64
Delay-Class Shaper C
70
68
SCHEDULER
Class Queue 1
Timestamp_Reg_1
72
Class_Delay_Reg_1
74
70
72
76
Class Queue i
Timestamp_Reg_i
Class_Delay_Reg_i
Sorter
74
70
Class Queue C
Timestamp_Reg_C
72
Class_Delay_Reg_C
74
79
Bypass Queue
Selector Bypass Unit
78

FIG. 8

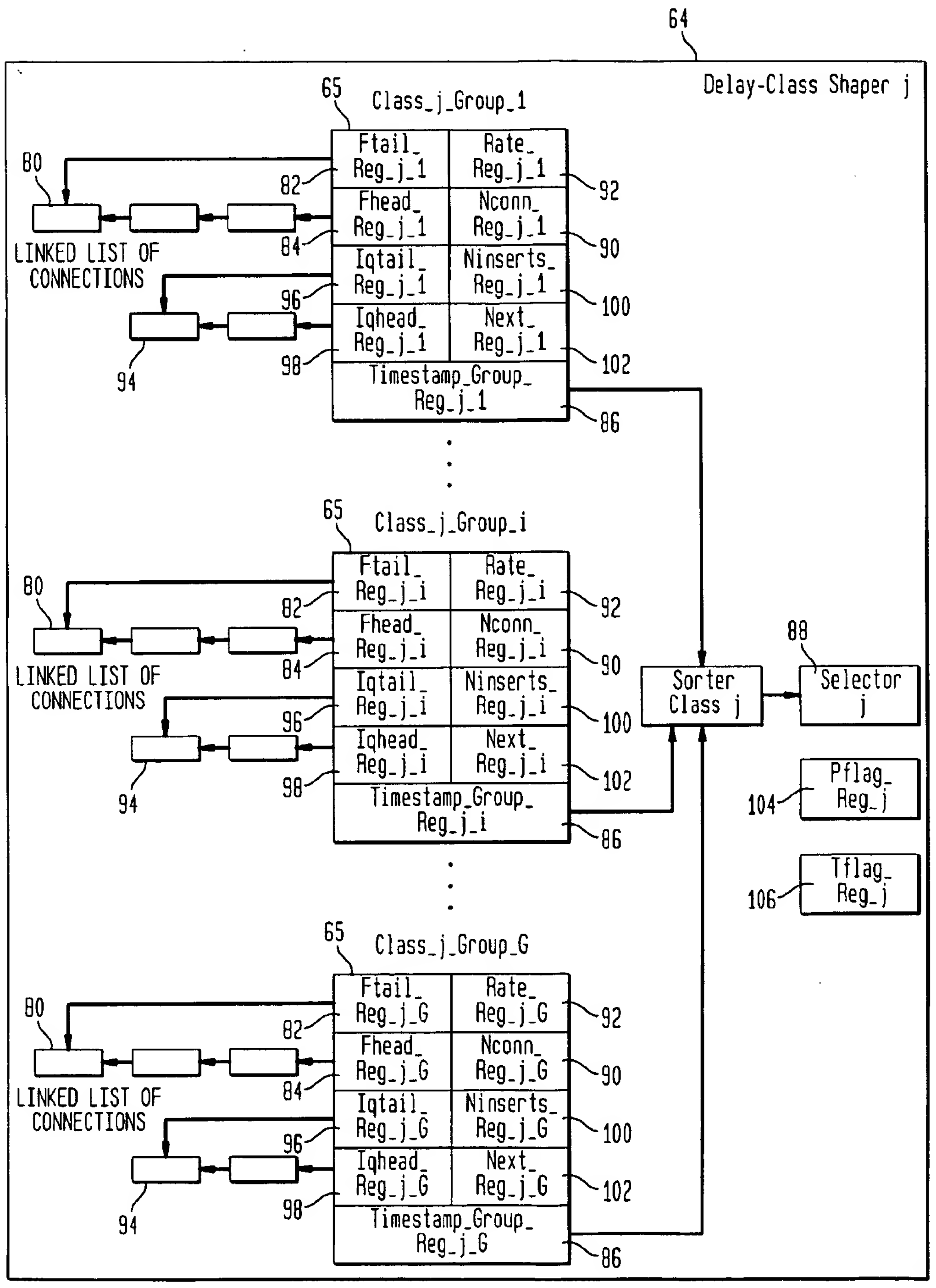

64
Delay-Class Shaper j
65
Class_j_Group_1
Ftail_ Reg_j_1
Rate_ Reg_j_1
Fhead_ Reg_j_1
Nconn_ Reg_j_1
Iqtail_ Reg_j_1
Ninserts_ Reg_j_1
Iqhead_ Reg_j_1
Next_ Reg_j_1
Timestamp_Group_ Reg_j_1
80
82
84
96
98
94
92
90
100
102
86
LINKED LIST OF CONNECTIONS
Class_j_Group_i
Ftail_ Reg_j_i
Rate_ Reg_j_i
Fhead_ Reg_j_i
Nconn_ Reg_j_i
Iqtail_ Reg_j_i
Ninserts_ Reg_j_i
Iqhead_ Reg_j_i
Next_ Reg_j_i
Timestamp_Group_ Reg_j_i
Class_j_Group_G
Ftail_ Reg_j_G
Rate_ Reg_j_G
Fhead_ Reg_j_G
Nconn_ Reg_j_G
Iqtail_ Reg_j_G
Ninserts_ Reg_j_G
Iqhead_ Reg_j_G
Next_ Reg_j_G
Timestamp_Group_ Reg_j_G
Sorter Class j
88
Selector j
104
Pflag_ Reg_j
106
Tflag_ Reg_j

FIG. 9A

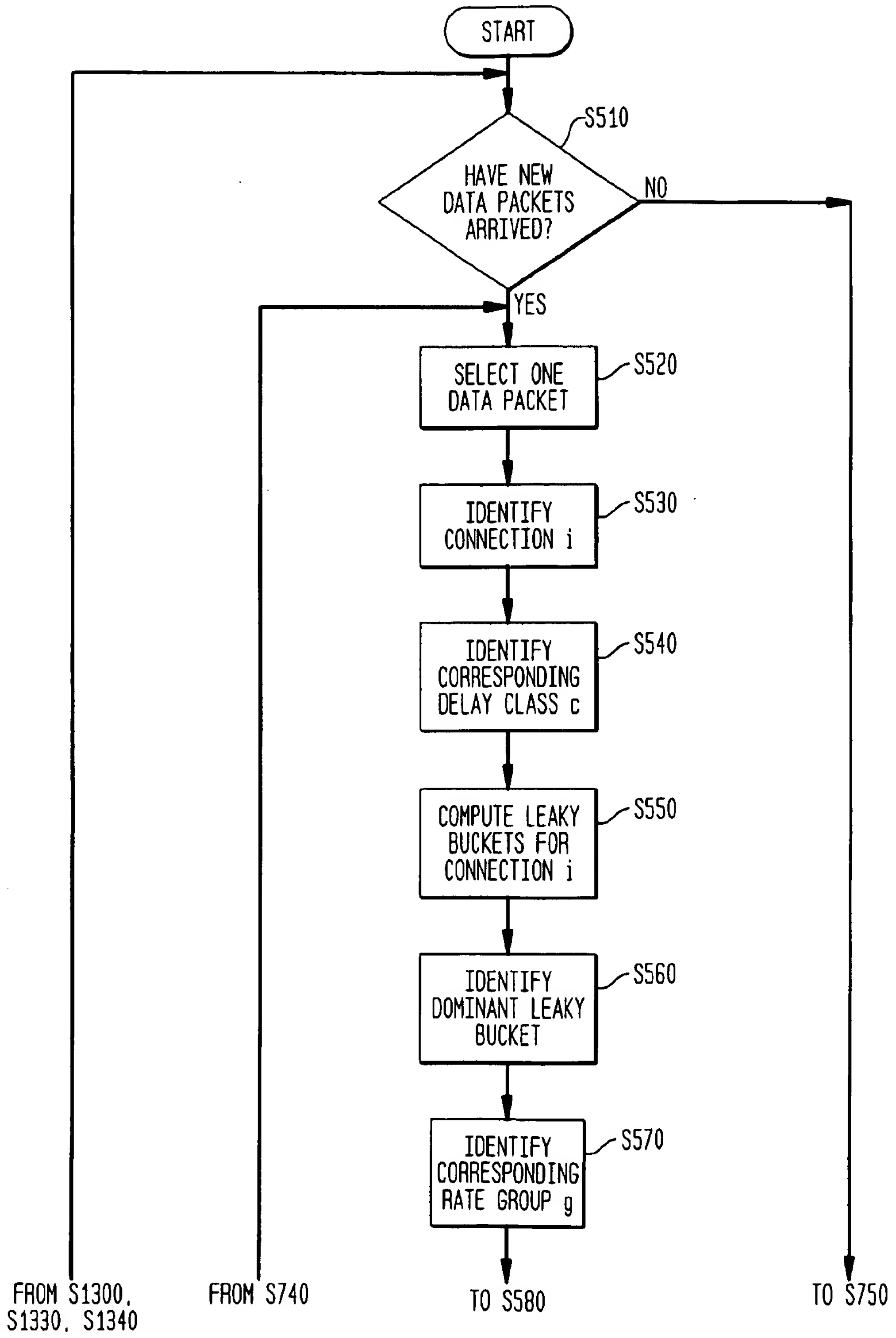

START
S510
HAVE NEW DATA PACKETS ARRIVED?
NO
YES
SELECT ONE DATA PACKET
S520
IDENTIFY CONNECTION i
S530
IDENTIFY CORRESPONDING DELAY CLASS c
S540
COMPUTE LEAKY BUCKETS FOR CONNECTION i
S550
IDENTIFY DOMINANT LEAKY BUCKET
S560
IDENTIFY CORRESPONDING RATE GROUP g
S570
FROM S1300, S1330, S1340
FROM S740
TO S580
TO S750

FIG. 9B

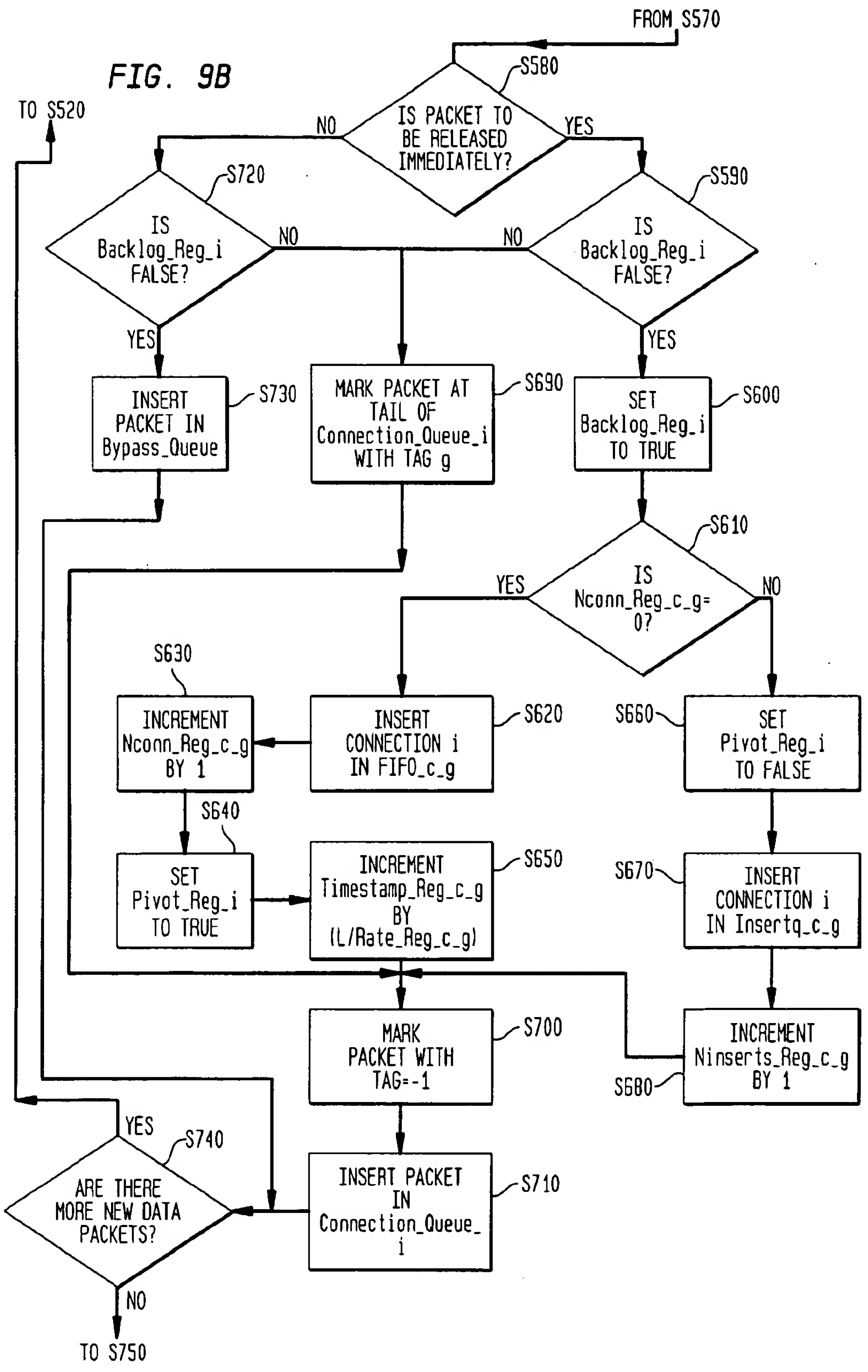

FROM S570
S580
IS PACKET TO BE RELEASED IMMEDIATELY?
NO
YES
TO S520
S720
IS Backlog_Reg_i FALSE?
NO
YES
S590
IS Backlog_Reg_i FALSE?
NO
YES
INSERT PACKET IN Bypass_Queue
S730
MARK PACKET AT TAIL OF Connection_Queue_i WITH TAG g
S690
SET Backlog_Reg_i TO TRUE
S600
S610
IS Nconn_Reg_c_g= 0?
YES
NO
S630
INCREMENT Nconn_Reg_c_g BY 1
INSERT CONNECTION i IN FIFO_c_g
S620
S660
SET Pivot_Reg_i TO FALSE
S640
SET Pivot_Reg_i TO TRUE
INCREMENT Timestamp_Reg_c_g BY (L/Rate_Reg_c_g)
S650
S670
INSERT CONNECTION i IN Insertq_c_g
MARK PACKET WITH TAG=-1
S700
INCREMENT Ninserts_Reg_c_g BY 1
S680
YES
S740
ARE THERE MORE NEW DATA PACKETS?
INSERT PACKET IN Connection_Queue_i
S710
NO
TO S750

FIG. 9C

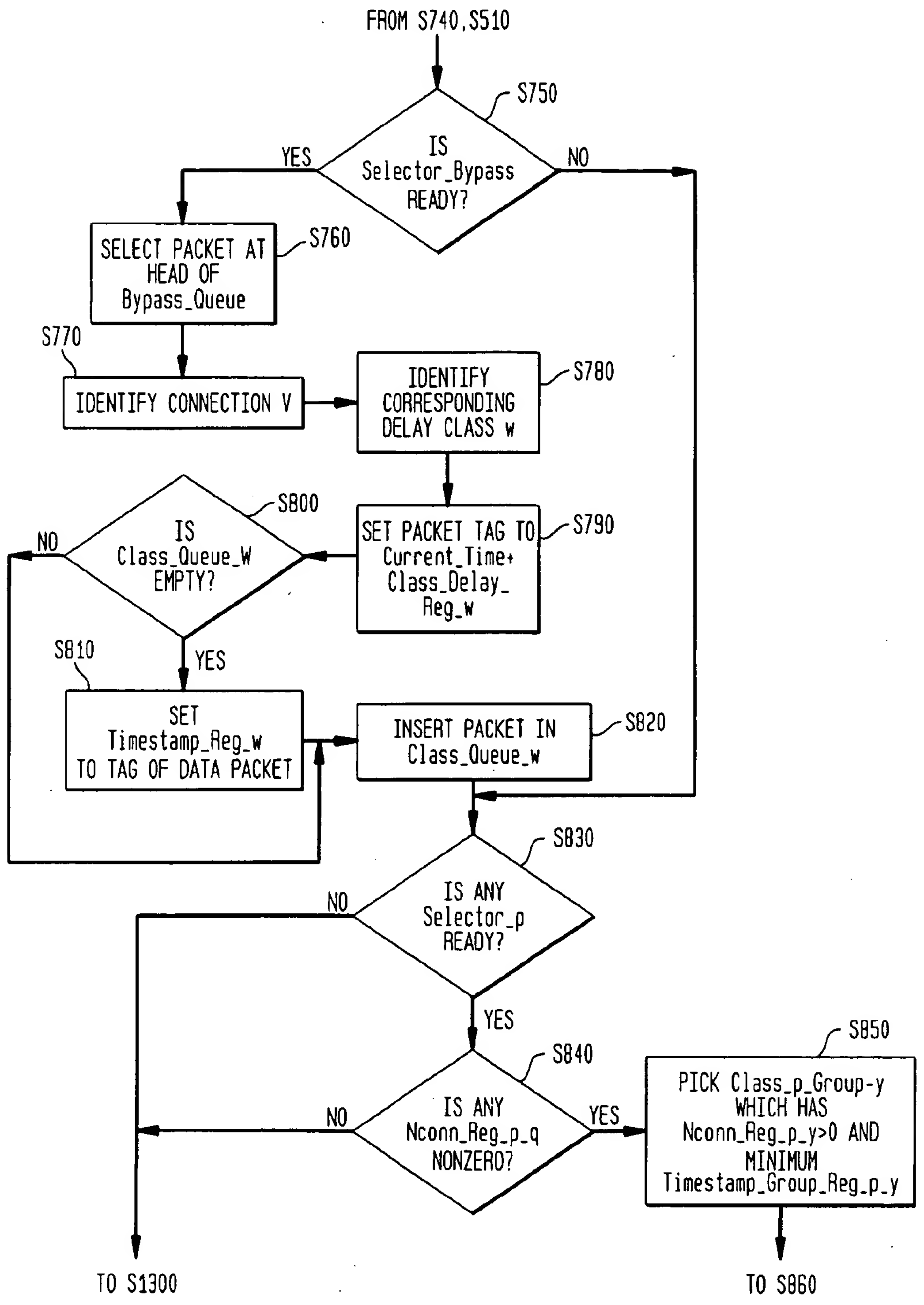

FROM S740,S510
S750
IS Selector_Bypass READY?
YES
NO
SELECT PACKET AT HEAD OF Bypass_Queue
S760
S770
IDENTIFY CONNECTION V
IDENTIFY CORRESPONDING DELAY CLASS w
S780
S800
IS Class_Queue_W EMPTY?
NO
SET PACKET TAG TO Current_Time+ Class_Delay_ Reg_w
S790
S810
YES
SET Timestamp_Reg_w TO TAG OF DATA PACKET
INSERT PACKET IN Class_Queue_w
S820
S830
IS ANY Selector_p READY?
NO
YES
S840
IS ANY Nconn_Reg_p_q NONZERO?
NO
YES
S850
PICK Class_p_Group-y WHICH HAS Nconn_Reg_p_y>0 AND MINIMUM Timestamp_Group_Reg_p_y
TO S1300
TO S860

FIG. 9D

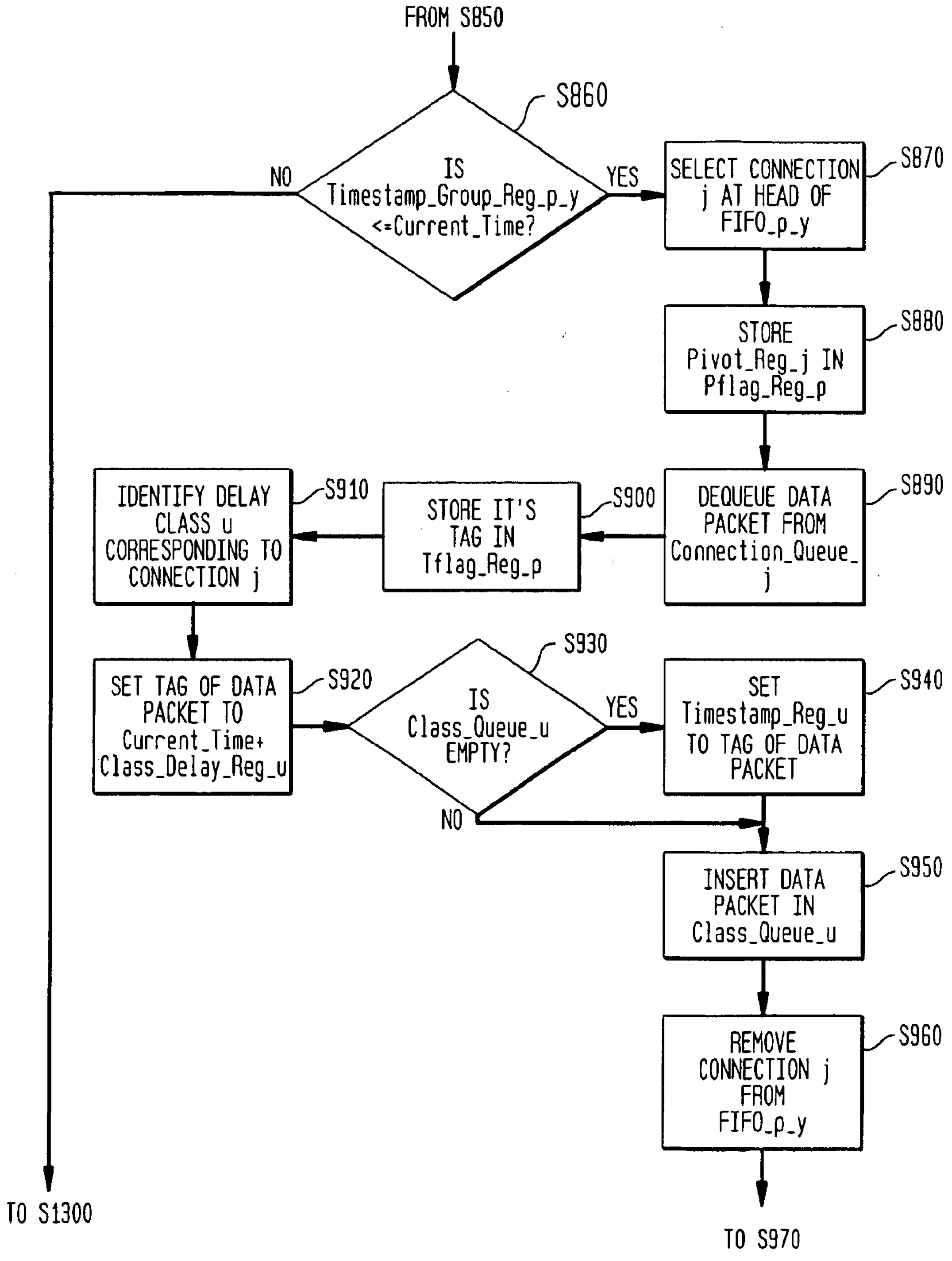

FROM S850
S860
IS Timestamp_Group_Reg_p_y <=Current_Time?
NO
YES
SELECT CONNECTION j AT HEAD OF FIFO_p_y
S870
STORE Pivot_Reg_j IN Pflag_Reg_p
S880
DEQUEUE DATA PACKET FROM Connection_Queue_j
S890
STORE IT'S TAG IN Tflag_Reg_p
S900
IDENTIFY DELAY CLASS u CORRESPONDING TO CONNECTION j
S910
SET TAG OF DATA PACKET TO Current_Time+ Class_Delay_Reg_u
S920
IS Class_Queue_u EMPTY?
S930
YES
NO
SET Timestamp_Reg_u TO TAG OF DATA PACKET
S940
INSERT DATA PACKET IN Class_Queue_u
S950
REMOVE CONNECTION j FROM FIFO_p_y
S960
TO S1300
TO S970

FIG. 9E

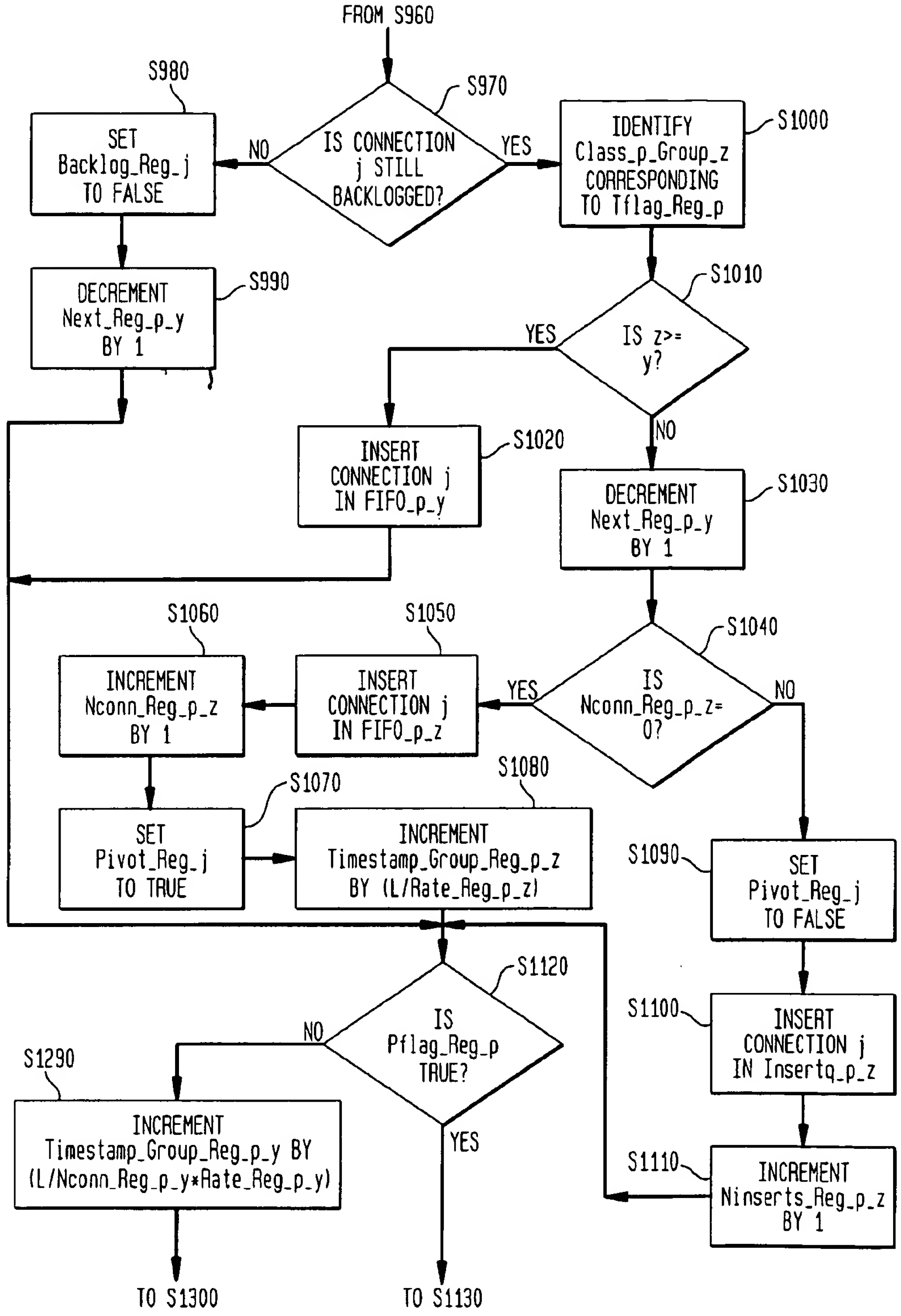

FROM S960
S970
IS CONNECTION j STILL BACKLOGGED?
NO
YES
S980
SET Backlog_Reg_j TO FALSE
S990
DECREMENT Next_Reg_p_y BY 1
S1000
IDENTIFY Class_p_Group_z CORRESPONDING TO Tflag_Reg_p
S1010
IS z>= y?
YES
NO
S1020
INSERT CONNECTION j IN FIFO_p_y
S1030
DECREMENT Next_Reg_p_y BY 1
S1040
IS Nconn_Reg_p_z= 0?
YES
NO
S1050
INSERT CONNECTION j IN FIFO_p_z
S1060
INCREMENT Nconn_Reg_p_z BY 1
S1070
SET Pivot_Reg_j TO TRUE
S1080
INCREMENT Timestamp_Group_Reg_p_z BY (L/Rate_Reg_p_z)
S1090
SET Pivot_Reg_j TO FALSE
S1100
INSERT CONNECTION j IN Insertq_p_z
S1110
INCREMENT Ninserts_Reg_p_z BY 1
S1120
IS Pflag_Reg_p TRUE?
NO
YES
S1290
INCREMENT Timestamp_Group_Reg_p_y BY (L/Nconn_Reg_p_y*Rate_Reg_p_y)
TO S1300
TO S1130

FIG. 9F

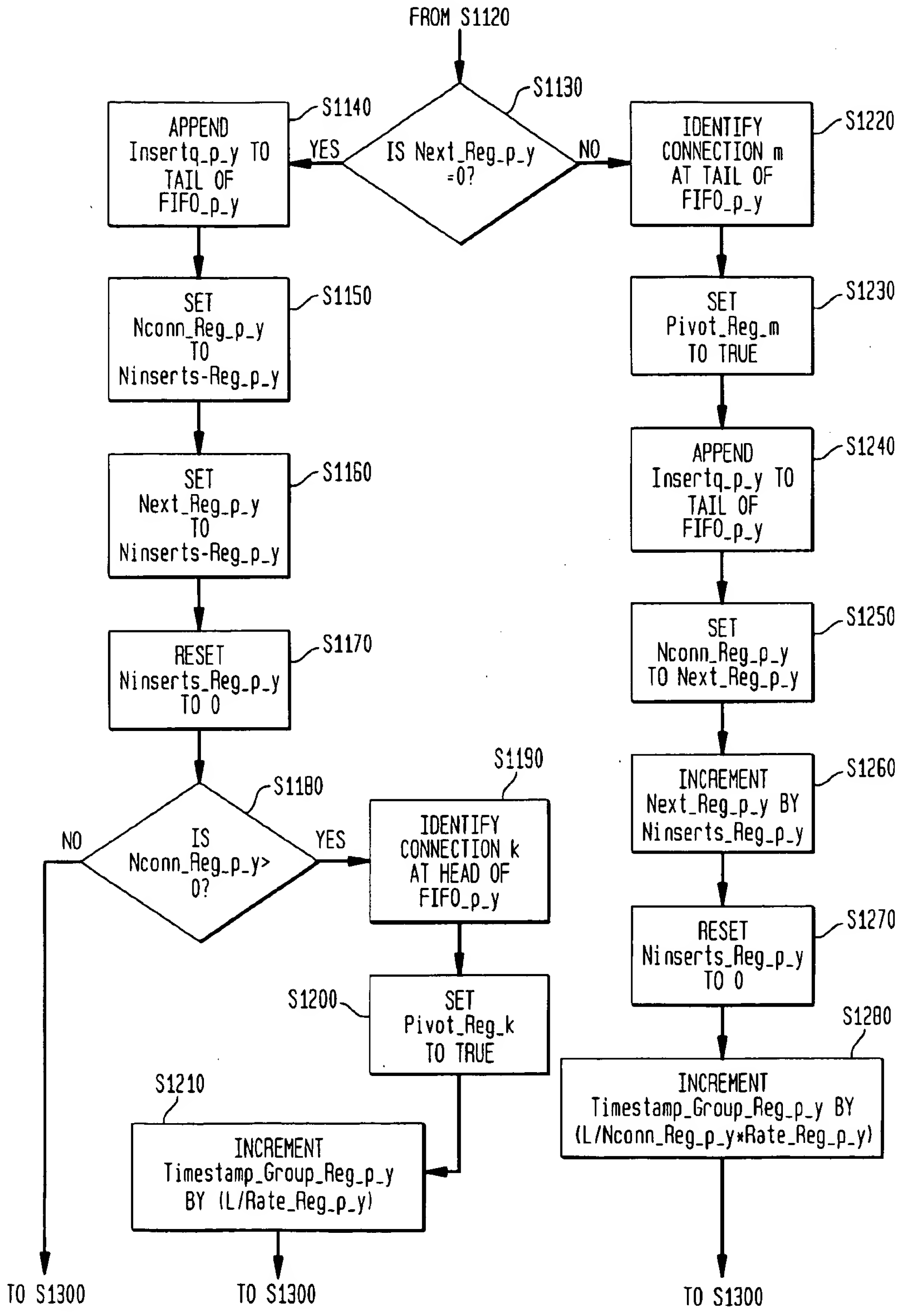

FROM S1120
S1130
IS Next_Reg_p_y =0?
YES
NO
S1140
APPEND Insertq_p_y TO TAIL OF FIFO_p_y
S1150
SET Nconn_Reg_p_y TO Ninserts-Reg_p_y
S1160
SET Next_Reg_p_y TO Ninserts-Reg_p_y
S1170
RESET Ninserts_Reg_p_y TO 0
S1180
IS Nconn_Reg_p_y> 0?
NO
YES
S1190
IDENTIFY CONNECTION k AT HEAD OF FIFO_p_y
S1200
SET Pivot_Reg_k TO TRUE
S1210
INCREMENT Timestamp_Group_Reg_p_y BY (L/Rate_Reg_p_y)
TO S1300
TO S1300
S1220
IDENTIFY CONNECTION m AT TAIL OF FIFO_p_y
S1230
SET Pivot_Reg_m TO TRUE
S1240
APPEND Insertq_p_y TO TAIL OF FIFO_p_y
S1250
SET Nconn_Reg_p_y TO Next_Reg_p_y
S1260
INCREMENT Next_Reg_p_y BY Ninserts_Reg_p_y
S1270
RESET Ninserts_Reg_p_y TO 0
S1280
INCREMENT Timestamp_Group_Reg_p_y BY (L/Nconn_Reg_p_y*Rate_Reg_p_y)
TO S1300

FIG. 9G

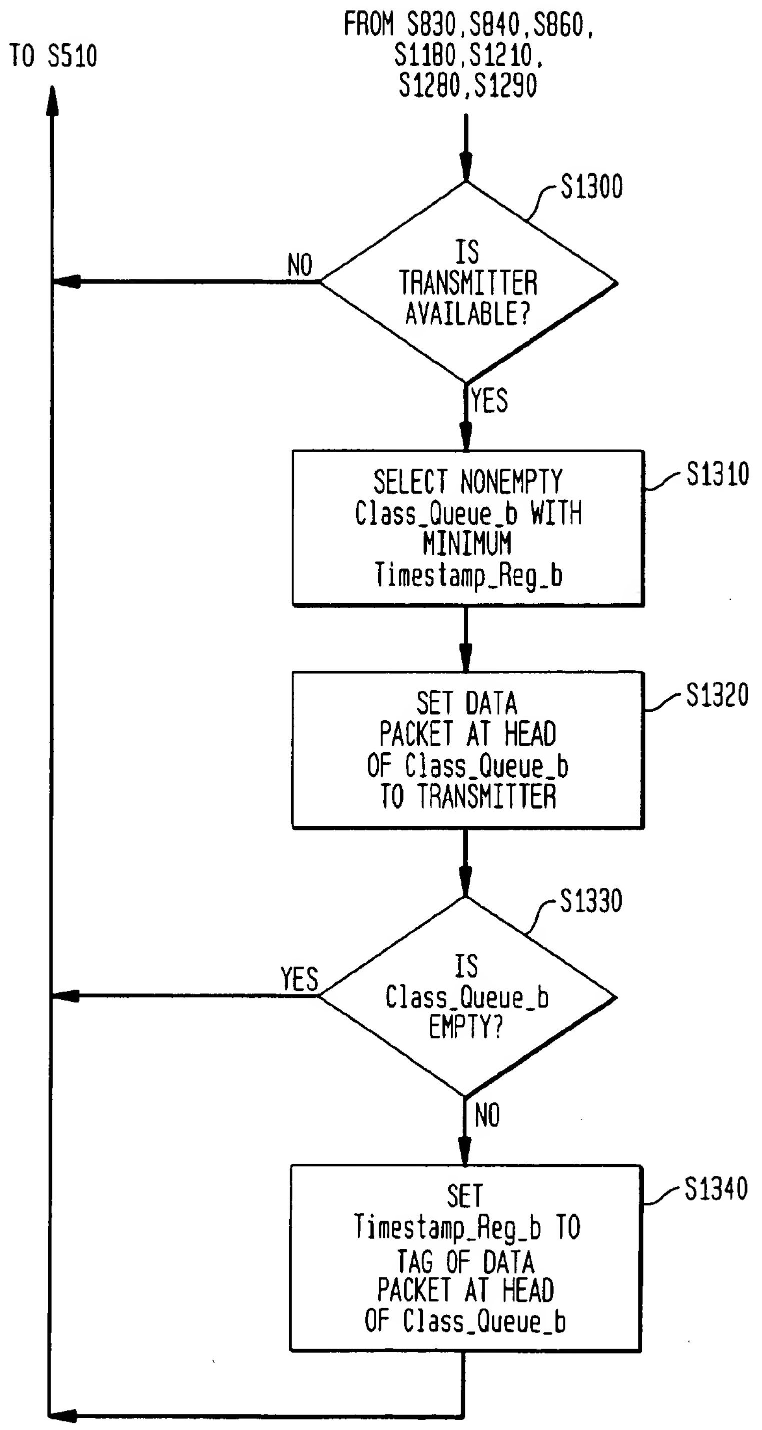
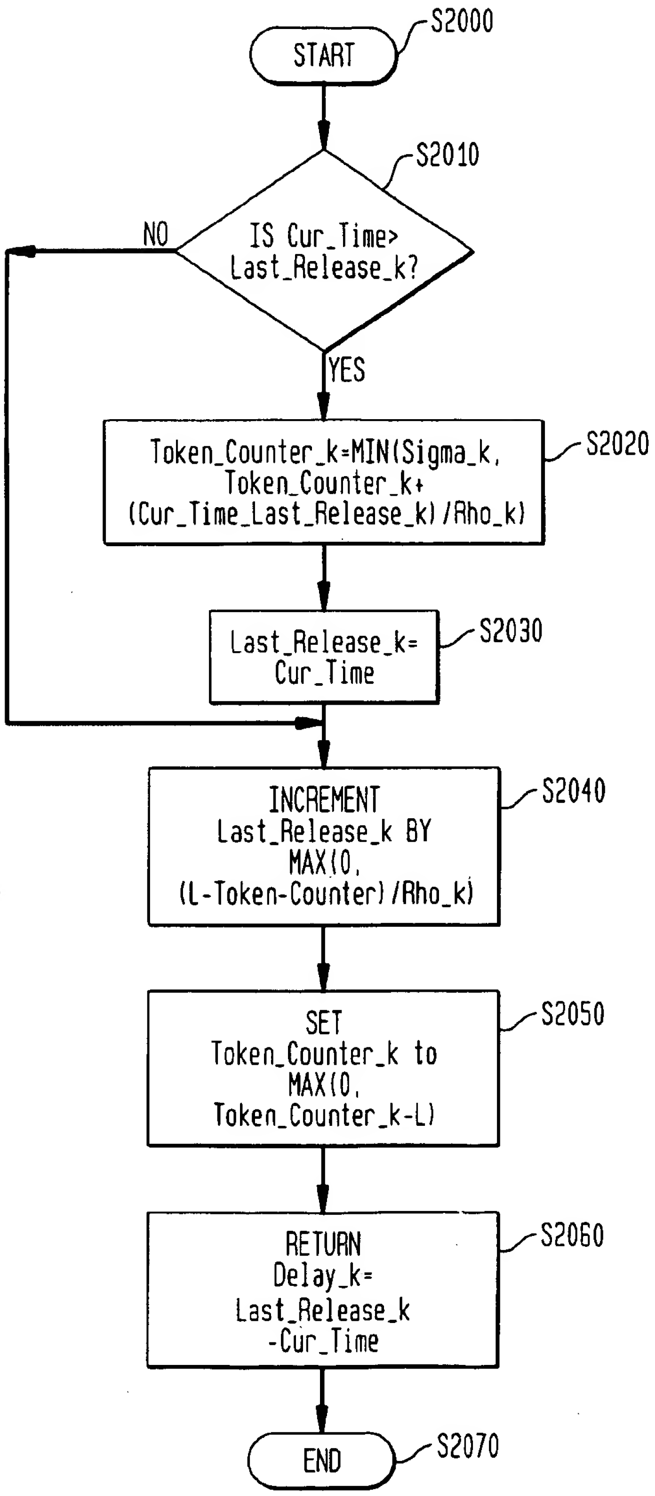

TO S510
FROM S830,S840,S860, S1180,S1210, S1280,S1290
S1300
IS TRANSMITTER AVAILABLE?
NO
YES
S1310
SELECT NONEMPTY Class_Queue_b WITH MINIMUM Timestamp_Reg_b
S1320
SET DATA PACKET AT HEAD OF Class_Queue_b TO TRANSMITTER
S1330
IS Class_Queue_b EMPTY?
YES
NO
S1340
SET Timestamp_Reg_b TO TAG OF DATA PACKET AT HEAD OF Class_Queue_b

FIG. 10


START
S2000
S2010
IS Cur_Time> Last_Release_k?
NO
YES
Token_Counter_k=MIN(Sigma_k, Token_Counter_k+ (Cur_Time_Last_Release_k)/Rho_k)
S2020
Last_Release_k= Cur_Time
S2030
INCREMENT Last_Release_k BY MAX(0, (L-Token-Counter)/Rho_k)
S2040
SET Token_Counter_k to MAX(0, Token_Counter_k-L)
S2050
RETURN Delay_k= Last_Release_k -Cur_Time
S2060
END
S2070

GUARANTEEING DATA TRANSFER DELAYS IN DATA PACKET NETWORKS USING EARLIEST DEADLINE FIRST PACKET SCHEDULERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of the filing date of U.S. provisional application No. 60/085,547, filed on May 15, 1998 as attorney docket no. Chiussi 12-1.

FIELD OF THE INVENTION

The present invention relates to a system for scheduling packets in packet networks and, more particularly, to guaranteeing data transfer delays from data sources to destinations.

BACKGROUND

FIG. 1 shows a packet network in which a plurality of switches **2** are connected to each other by communication links **8**. A number of data sources **4** and destinations **6** are connected to the communication switches **2**. From time to time, a network connection is established or torn down from each of these data sources **4** to a corresponding destination. The connection establishment process involves one of the data sources **4** sending a packet including control information that indicates one of the destinations **6** to which it desires the connection and the desired envelope of the data traffic it agrees to send on the connection, along with the desired delay bounds at each of the communication switches **2** on the path to the destination. The above desired connection and envelope are specified in terms of leaky-bucket parameters as disclosed in R. Cruz, "A Calculus for Network Delay, Part II: Network Analysis," *IEEE Transactions on Information Theory*, pp. 121–141, January 1991. For the tear-down of a connection, the data source sends a packet including control information indicating that the connection needs to be torn down.

When one of the switches **2** in the network receives a data packet indicating that a connection needs to be established, the switch executes a call admission control (CAC) procedure to determine whether or not the delay required by the connection can be guaranteed by the network, If the result of such a procedure in every switch on the path of the connection in the network indicates that the delay can be guaranteed by the network, then the connection is accepted in the network. On the other hand, if the result of such a procedure in at least one of the switches **2** on the path of the connection in the network indicates that the delay cannot be guaranteed by the network, then the connection is not accepted in the network.

The provision of quality-of-service (QoS) guarantees, such as bandwidth, delay, jitter, and cell loss, to applications of widely different characteristics is a primary objective in emerging broadband packet-switched networks. In such networks, packet-scheduling disciplines are necessary to satisfy the QoS requirements of delay-sensitive applications, and they ensure that real-time traffic and best-effort traffic can coexist on the same network infrastructure. Among the scheduling algorithms that have been proposed in literature, two classes of schemes have become popular: those based on generalized processor sharing (GPS) and those based on earliest deadline first (EDF). For a survey of these algorithms, see S. Keshav, *An Engineering Approach to Computer Networking. ATM Networks, the Internet, and the Telephone Network*, Addison-Wesley, Ithaca, N.Y., 1996; H. Zhang, "Service Disciplines for Guaranteed Performance Service in Packet-Switching Networks," *Proceedings of the IEEE*, pp. 1374–1396, October 1995.

EDF scheduling has been known for many years in the context of processor scheduling as disclosed in C. L. Liu and J. W. Wayland, "Scheduling algorithms for multiprogramming in a hard real time environment," *Journal of ACM*, pp. 46–61, January 1973. Furthermore, it has been more recently proposed as a possible packet-scheduling discipline for broadband networks as disclosed in D. Ferrari and D. Verma, "A Scheme for Real-Time Channel Establishment in Wide-Area Networks," *IEEE Jour. Sel. Areas Commun.*, pp. 368–379, April 1990; D. Verma, H. Zhang, D. Ferrari, "Guaranteeing Delay Jitter Bounds in Packet Switching Networks," *Proc. TRICOMM*, pp. 35–46, Chapel Hill, N.C., October 1991. The EDF scheduling discipline generally works as follows: each connection i at a switch k is associated with a local delay deadline d_i^k; then an incoming packet of connection i arriving to the scheduler at time t is stamped with a deadline $t+d_i^k$, and packets in the scheduler are served by increasing order of their deadline.

For a single switch, EDF is known to be the optimal scheduling policy as disclosed in L. Georgiadis, R. Guerin, and A. Parekh, "Optimal Multiplexing on a Single Link: Delay and Buffer Requirements," RC 19711 (97393), *IBM T. J.*, Watson Research Center, August 1994; J. Liebeherr, D. Wrege, and D. Ferrari, "Exact Admission Control for Networks with a Bounded Delay Service," *IEEE/ACM Trans. Networking*, pp. 885–901, December 1996. Optimality is defined in terms of the schedulable region associated with the scheduling policy. Given N connections with traffic envelopes $\overline{A}_i(t)$ ($i=1, 2, \ldots, N$) sharing an output link, and given a vector of delay bounds $\vec{D}=(d_1, d_2, \ldots, d_N)$, where d_i is an upper bound on the scheduling delay that packets of connection i can tolerate, the schedulable region of a scheduling discipline π is defined as the set of all vectors $\vec{D}$ that are schedulable under π. EDF has the largest schedulable region of all scheduling disciplines, and its non-preemptive version (NPEDF) has the largest schedulable region of all the non-preemptive policies. The schedulable region of the NPEDF policy consists of those vectors that satisfy the following constraints:

$$\frac{L}{r} \le d_1 \tag{1}$$

$$L + \sum_{i=1}^{N} \overline{A}_i(t-d_i) \le rt,\ \frac{L}{r} \le t \le d_N \tag{2}$$

$$\sum_{i=1}^{N} \overline{A}_i(t-d_i) \le rt,\ t \ge d_N \tag{3}$$

where $d_i \leqq d_2 \leqq \ldots \leqq d_N$, L is the packet size (if the packet size is variable, then L is the maximum packet size), r is the link rate, and $\overline{A}_i(t)=0$ for $t<0$. Within a single node, once the traffic envelopes are known, a 100% link utilization can be achieved (at least in principle) with this characterization.

The difficulties arise in a multi-switch or multi-node network where the traffic envelopes are no longer determined at the inputs of the nodes inside the network, and the interactions that distort the traffic are not easily characterizable. This problem is not peculiar of EDF, but is common to any scheduling discipline. As a general framework to handle the multi-node problem, H. Zhang and D. Ferrari, "Rate-Controlled Service Disciplines," *Jour. High Speed*

Networks, pp. 389–412, 1994, propose a class of schemes called rate-controlled service (RCS) disciplines which reshape the traffic at each hop within the network. As schematically shown in FIG. **2**, an RCS server **10** has two components: a shaper **12** which reshapes the traffic of each connection and a scheduler **14** which receives packets released by the shaper and schedules them according to a specific scheduling discipline, such as EDF as disclosed in L. Georgiadis, R. Guerin, V. Peris, and K. Sivarajan, "Efficient Network QoS Provisioning Based on per Node Traffic Shaping," *IEEE/ACM Trans. Networking*, pp. 482–501, August 1996 ("Georgiadis et al."), who build upon this model and derive expressions for the end-to-end delay bounds in terms of the shaper envelope and scheduling delay at each node. They also show the following useful properties of RCS.

Identical shapers at each switch along the path of a connection i (i.e., shapers having identical shaper envelopes for connection i) produce end-to-end delays that are no worse than those produced by different shapers at each switch. Therefore, for any given connection, identical shapers can be used at each node. This shaper envelope common to all shapers for connection i is denoted as $\overline{E}_i$ (t).

The end-to-end delay bound for connection i is given by:

$$\overline{D}_i = D(\overline{A}_i \| \overline{E}_i) + \sum_{k=1}^{k_i} d_i^k \tag{4}$$

where $\overline{D}_i$=D($\overline{A}_i\|\overline{E}_i$) denotes the maximum shaper delay, and d_i^k is the bound on the scheduler delay for packets of connection i at the k-th switch on its path. The maximum shaper delay is incurred only once and is independent of the number of nodes on the path. The total scheduler delay is the sum of the individual scheduling delays d_i^k at each node. When EDF scheduling is used together with per-node reshaping (this combination is referred to as RC-EDF), and the delay components in Equation (4) are properly chosen, the same delay bounds as GPS can be achieved.

The above properties combined with Equations (1–3) enable a call admission control (CAC) framework that decides if connections may or may not enter the network while ensuring that end-to-end performance constraints are met. How CAC works is first analyzed for an isolated EDF scheduler, and then the analysis proceeds to the multi-node case.

In a single switch, Equations (2) and (3) immediately lead to a CAC scheme. With RC-EDF, given the traffic envelope $\overline{E}_i$ (t) (enforced by the shaper) and local delay bound for each of the connections being multiplexed on a link of the switch, the equations are combined into:

$$L + \sum_{i=1}^{N} \overline{E}_i(t-d_i) \le rt, \; t \ge \frac{L}{r} \tag{5}$$

where $d_i \geqq L/r$, i=1,2, . . . N.

Equation (5) can be graphically interpreted to yield a simple single-switch CAC scheme. $\overline{E}_i$ (t–d_i) is the curve obtained by shifting the connection i arrival envelope curve $\overline{E}_i$(t) to the right by its delay bound d_i, and denotes the minimal service $\hat{S}_i$ (t) required by connection i in order to meet its local delay bound. The aggregate service demand of all connections at the scheduler is thus given by

$$S(t) = L + \sum_{i=1}^{N} \hat{S}_i(t)$$

where the term L accounts for the non-preemptive nature of the scheduler). If the aggregate service demand service $\hat{S}$(t) never exceeds the server capacity given by R(t)=rt for t≧L/r, the packets can be scheduled such that none misses its deadline. FIG. **3** illustrates the service capacity and service demand curves for a simple example with two leaky-bucket constrained connections. Since the following relationship, S(t)=L+$\overline{E}_1$ (t–d_1)+E_2(t–d_2)≦R(t) holds for all t≧L/r, the two calls can be admitted with guaranteed delay bounds d_1 and d_2.

The extension of this scheme to the multi-node case is as follows. For an incoming connection i with traffic arrival envelope at the edge of the network $\overline{A}_i$(t) and end-to-end delay requirement d_i, the end-to-end CAC algorithm performs the following steps to determine if the connection can be accommodated in the network:

1. It chooses an appropriate shaper with envelope $\overline{E}_i$(t) for the connection, and computes the corresponding delay D($\overline{A}_i\|\overline{E}_i$). The delay computation is described in Georgiadis et al.
2. The k-th switch on the path is assigned a delay bound d_i^k such that

$$D(\overline{A}_i \| \overline{E}_i) + \sum_k d_i^k = \overline{D}_i \cdot A$$

single-node schedulability check according to the schedulability criterion of Equation (5) is performed (using envelope $\overline{E}_i$(t) and delay bound d_i^k) at each switch on the path.
3. The connection is admitted only if every switch on the path can accommodate the connection.

The results in Georgiadis et al. can be used for choosing the shaper envelope and for splitting the total scheduling delay among the schedulers on the path. For leaky-bucket-constrained sources with traffic arrival envelope $\overline{A}_i(t)=\sigma_i+\rho_i t$, generalized processor sharing performance can be matched by choosing shaper envelope $\overline{E}_i(t)=(L+g_i t, \sigma_i+\rho_i t)$, and assigning local delay bound $d_i^k=L/g_i+L/r^k$, to the k-th switch on the path, where r^k is the link rate and g_i is the rate allocated to the connection at each switch.

A potentially serious problem is that the implementation of an RC-EDF server, which consists of a traffic shaper and an EDF scheduler, can be quite complex. Without techniques to reduce this complexity, the scheme would be unaffordable in practice for application to current packet switches.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and an apparatus to implement a EDF-related packet server of minimum complexity, comprising a shaper and a scheduler, which guarantees a small value of the maximum data transfer delay,to each connection.

The EDF-related packet server (alternately called the RC-EDF server) provides a shaper and a scheduler. In accordance with a first aspect of the invention, the shaper holds and releases packets such that the traffic belonging to each connection exiting the shaper conforms to a pre-specified envelope, while the scheduler at each-scheduling instant selects from among the packets released by the shaper the one to be transmitted next on the outgoing link.

To reduce the implementation complexity of both the shaper and the scheduler, the RC-EDF server supports a (relatively small) discrete set of delay classes. Each delay class is associated with a delay value, and this delay value corresponds to the delay guarantee provided by the scheduler to the packets of each connection contained in the delay class.

The shaper provides one shaping structure per delay class (each of such structures is referred to as delay class shaper), each of which shapes all connections corresponding to a specific delay class. Each delay class shaper supports a discrete number of shaping rates, each of which is associated with a first-in-first-out (FIFO) queue. Each shaping rate corresponds to a possible value of the slope corresponding to a piece of a piecewise-linear envelope. Each connection which has at least one packet in the shaper is associated with exactly one of the above-mentioned FIFO queues. The delay class shaper has a two-level hierarchical structure. The lower level of the hierarchy uses FIFO queues, one per rate. At the higher level of the hierarchy, the timestamps associated with each FIFO queue are used to select from among the different FIFO queues for that delay class. Based on the timestamps, the delay-class shaper selects one FIFO queue and sends the first packet of the connection at the head of the selected FIFO to the scheduler.

The scheduler maintains a queue of packets for each delay class. Each packet is associated with a timestamp derived from its release time by the shaper and the delay bounds guaranteed to the connection. A sorter selects from among the packets at the head of the FIFOs the one with the minimum timestamp for transmission on the outgoing link.

In accordance with another aspect of the invention, the EDF-related packet server provides a different shaper from the embodiment according to the first aspect of the invention. The scheduler is identical to the embodiment according to the first aspect of the invention. The shaper provides one shaping structure per delay class (referred to as delay class shaper), each of which shapes all connections corresponding to the delay class. Each delay class shaper supports a discrete number of shaping rates, each of which is associated with a FIFO queue. Each connection that has at least one packet in the shaper could be associated with a multiplicity of the FIFO queues. This is in contrast to the first aspect of the invention where each connection with at least one packet in the shaper is associated with exactly one FIFO queue. The delay class shaper has a two-level hierarchical structure. The lower level of the hierarchy uses FIFO queues, one per rate. At the higher level of the hierarchy, the timestamps associated with each FIFO queue are used to select from among the different FIFO queues for that delay class.

These and other aspects of the invention will become apparent in the ensuing detailed description taken in conjunction with the accompanying figures, which disclose a number of preferred embodiments of the invention.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 illustrates a packet network in which a number of switches, data sources, and destinations are connected.

FIG. 2 shows a schematic of the rate controlled service (RCS) discipline server illustrating the concept of traffic reshaping at each switch in the data network.

FIG. 3 illustrates an example of the schedulability tests for a single node.

FIG. 4 illustrates a communication switch in the packet network.

FIG. 5 is a block diagram of the communication link interface according to a first embodiment of the present invention for scheduling the transmission of data packets in a communication link.

FIG. 6 is a block diagram of the connection controller that is part of the communication link interface of FIG. 5.

FIG. 7 is a block diagram of the server that is part of the communication link interface of FIG. 5.

FIG. 8 is a block diagram of the delay class shaper that is part of the server of FIG. 7.

FIGS. 9A–9G show in flowchart form a first method of scheduling the transmission of data packets in a communication link interface of FIG. 5 in accordance with the principles of the present invention.

FIG. 10 shows in flowchart form a method of computing the release time of an incoming packet by a leaky bucket in accordance with the principles of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 4 shows a communication switch 20 in a packet network. The communication switch 20 includes a plurality of input communication link interfaces 24, each of which connects a plurality of input links 22 to an output link 27. The output links 27 of these input communication link interfaces 24 serve as inputs to a switch fabric 26. The switch fabric 26 processes the link signals and outputs another set of output links 28 to a plurality of output communication link interfaces 30. The output communication link interfaces 30 output ultimate output link signals 32 of the communication switch 20.

FIG. 5 shows a block diagram illustrating a first embodiment of each input communication link interface 24 of FIG. 4 according to the present invention. The input communication link interface 24 includes a data packet receiver 40, which receives the data packets arriving from the input links 22. The receiver 40 uses the contents of the connection identifier field contained in the header of each packet to identify its respective connection i. All packets that the receiver 40 receives have the same length. The receiver 40 thereafter sends each packet to a corresponding connection controller 42. Each connection controller 42 stores a set of information related to a particular connection i. A leaky-bucket processor 44 determines a shaping rate r_i that a particular packet desires. Subsequently, a delay-class and rate-group identifier 46 determines a delay class j to which the connection belongs as well as an index i corresponding to the shaping rate r_i. A server 48 groups connections into a discrete set of a relatively small, predetermined number of delay classes. Finally, a transmitter 50 transmits the output of the server 48 to the corresponding output link 27.

FIG. 6 illustrates one preferred embodiment of each connection controller 42 of FIG. 5 for a connection i according to the current invention. In other words, for each connection, the same structure is duplicated. Each connection controller 42 includes the following:

(a) a connection queue 52, which is used to store the received data packets of connection i, with registers Qtail_Reg 60 and Qhead_Reg 62 containing pointers to the head and tail, respectively, of the connection queue 52,

(b) a register Backlog_Reg 54, which indicates whether or not the connection is backlogged (i.e., has at least one packet in its queue),

(c) a register Shaper_Index_Reg 56, which stores an index of the rate group to which the connection belongs, and

(d) a register Pivot_Reg **58**, which indicates whether or not the connection is a pivot (described below).

FIG. **7** illustrates one preferred embodiment of the server **48** of FIG. **5** according to the current invention. In general, the server **48** groups connections into a discrete set of a relatively small, predetermined number C of delay classes. The server **48** includes at least two main components: a shaper **63** having C delay-class shapers **64** and a scheduler **68**. Each delay class is associated with a delay value, and this delay value corresponds to the delay guarantee provided by the scheduler **68** to the packets of each connection in the delay class. The delay-class shapers **64** provide one scheduling structure per delay class.

Similarly, for each delay class, the scheduler **68** includes a class queue **70** for queuing data packets, a register Timestamp_Reg **72** for storing timestamp information, and a register Class_Delay_Reg **74** for storing guaranteed time-delay information. The server **48** also includes a sorter **76** for sorting the time-stamped information and a selector bypass unit **78** for inserting packet data from a bypass queue **79** into a corresponding class queue **70**.

When a packet arrives for connection at an input communication link interface **24** of FIG. **4**, the leaky-bucket processor **44** of FIG. **5** determines the shaping rate r_i which is desired by the packet. Additionally, the delay-class and rate-group identifier **46** determines a delay class j as well as a rate class i. If the leaky-bucket computation reveals that the packet is to be directly sent to a scheduler and the connection has no backlog, then the packet is inserted into the bypass queue **79** of FIG. **7**. The selector bypass unit **78** subsequently picks up the packet from the bypass queue **79** and inserts it at the tail of the appropriate class queue **70** in the scheduler **68**. If, on the other hand, the leaky-bucket computation reveals that the packet is not to be released immediately, or if the connection is backlogged (i.e., the corresponding connection queue **52** of FIG. **6** is not empty), then the packet at the tail of the corresponding connection queue **52** is marked with a tag equal to i, and the incoming packet is inserted at the tail of the corresponding connection queue **52**.

FIG. **8** illustrates one preferred embodiment of the structure of each delay-class shaper **64** of FIG. **7** according to the current invention. Each delay-class shaper **64** shapes all the connections in the corresponding delay class and supports a discrete number G of shaping rates r_1 through r_G. The total or overall rate at which each delay-class shaper **64** operates for releasing packets is equal to the link rate r. This is because the sum of the shaping rates of the connections in a delay class cannot exceed the link rate r. In the j-th delay-class shaper **64** shown in FIG. **8**, the i-th shaping rate r_i is associated with a corresponding rate group Class_j_Group_i **65**. Connections belonging to delay class j that need to be shaped at the rate r_i are queued in the FIFO_j_i **80**, which corresponds to the rate group Class_j_Group_i **65**, and the selection in the delay-class shaper j is performed only among connections at the head or top of FIFO_j_i **80**, where i=1 through G. In this preferred embodiment, each of the FIFOs **80** is implemented as a link list and has a corresponding tail pointer stored in register Ftail_Reg **82** for indicating the end of the queue and a corresponding head pointer stored in register Fhead_Reg **84** for indicating the top of the queue.

A selector **88**, located within delay-class shaper **64**, selects, at each time slot of length L/r, which is equal to the transmission time of a packet from the FIFOs **80** corresponding to the rate groups within the corresponding delay class j, the connection at the head of a nonempty FIFO **80** that has the minimum eligible timestamp stored in the corresponding register Timestamp_Group_Reg **86** among all rate groups belonging to that delay class j. An eligible queue timestamp is defined to be one whose value is not greater than the current time. Every time a FIFO is selected and a packet is released from the queue of the connection at the head of the selected FIFO into the scheduler **68** of FIG. **7**, the corresponding timestamp stored in Timestamp_Group_Reg **86** of FIG. **8** is incremented by $L/n_{ji}\ r_i$, where L is the packet length, n_{ji} is the number of connections queued in FIFO_J_i, and r_i is the rate corresponding to the rate group. The number of connections n_{ji} is stored in a corresponding register Nconn_Reg_j_i **90**, while the rate r_i is stored in the register Rate_Reg_j_i **92**. If the connection that has been selected remains backlogged and requires the same service rate r_i as indicated by the tag associated with the packet, then the packet is reinserted at the tail of FIFO_j_i **80**.

Each connection is shaped according to a piecewise-linear shaping envelope, which is the combination of one or more leaky-bucket envelopes as disclosed in R. Cruz, "A Calculus for Network Delay, Part II: Network Analysis," *IEEE Transactions on Information Theory*, pp. 121–141, January 1991, and each of the leaky-bucket envelopes is associated with a corresponding shaping rate. Because the shaping envelopes for the connections are piecewise-linear functions, the desired shaping rate may change while a connection is backlogged. Consequently, a connection that is queued in a given FIFO corresponding to a particular rate group in a delay-class shaper may, once served, have to be queued in a different FIFO corresponding to a different rate group within the same delay-class shaper. Such an occurrence is referred to as a rate jump. These jumps are computed and stored, preferably within a tag portion of the packet by the leaky-bucket processor **44** of FIG. **5**.

To account for the variations in rate or rate jumps experienced by backlogged connections, the concept of a pivot connection is introduced to each of the rate groups having a nonempty FIFO_j_i **80** of FIG. **8**. Every nonempty FIFO_j_i **80** has one of its connections marked as a pivot, and a corresponding flag is stored by each connection controller **42** of FIG. **5** in a corresponding register Pivot_Reg **58** of FIG. **6**. Consecutive appearances of the pivot at the head of a FIFO_j_i **80** are separated by a L/r_i difference in the values in register Timestamp_Group_Reg **86** of FIG. **8**. Connections that are to be inserted into a nonempty FIFO_j_i **80** either by virtue of a rate jump or by becoming newly backlogged are stored in an auxiliary queue Insertq_j_i **94** of FIG. **8**. Registers Iqhead_Reg **98** and Iqtail_Reg **96** store pointers to the head and tail, respectively, of the corresponding auxiliary queue. The number of such connections in the auxiliary queue Insertq_j_i **94** are stored in the register Ninserts_Reg_j_i **100**. Insertq_j_i **94** is appended to FIFO_j_i **80** when the pivot makes an appearance at the head of FIFO_j_i **80**. Simultaneously, the register Nconn_Reg **90** is updated using the value stored in register Next_Reg **102**, which accounts for deletions from FIFO_j_i **80** and the register Ninserts_Reg **100**.

To properly cope with a change in the shaping rate among connections, a rate jump is performed only from a higher rate to a lower rate within a busy period for the connection. That is, a busy period is when the connection is continuously backlogged. If a packet for a connection arrives at the server while the connection is still backlogged and requests a shaping rate that is higher than the shaping rate requested by the previous packet for that connection, the connection continues to be served at the lower rate. However, a packet arriving to a non-backlogged connection is inserted in the shaping FIFO queue corresponding to its requested shaping rate, irrespective of whether or not the previous packet of the connection was served at a lower rate. The rationale behind this is justified by the observation that, in an ideal shaper, a connection with a leaky-bucket traffic envelope never increases its shaping rate while it is still backlogged.

The following tables summarize the various blocks and structures as shown in FIGS. **5–10**.

FIFO_c_g as stored in the register Nconn_Reg_c_g **90** is not zero, the register Pivot_Reg_i **58** of FIG. **6** is set to FALSE in step **S660** and the connection i is inserted into the auxiliary queue Insertq_c_g **94** of FIG. **8** in step **S670**. Consequently, the value of the register Ninserts_Reg_c_g **90** of FIG. **8** is incremented by one in step **S680**. After the packet is marked with TAG=−1 in step **S700**, the packet is inserted in connection queue i **52** of FIG. **6** in step **S710**. Lastly, it is checked whether or not there remains more new

<u>Delay-Class Shaper j 64 of FIGS. 7 and 8:</u>	
Timestamp_Group_Reg_j_g	Timestamp for Class j, Group g
Rate_Reg_j_g	Rate at which Class j, Group g shapes
Nconn_Reg_j_g	Number of connections in Class j, Group g
FIFO_j_g	FIFO of connections in Class j, Group g (Fhead_Reg_j_g and Ftail_Reg_j_g contain pointers to the head and tail, respectively)
Insertq_j_g	Queue of connections waiting for insertion in Class j, Group g FIFO (Iqhead_Reg_j_g and Iqtail_Reg_j_g contain pointers to the head and tail, respectively)
Ninserts_Reg_j_g	Number of connections in insertion queue
Next_Reg_j_g	Number of connections in FIFO for next round
Pflag_Reg_j	Register for temporary storage of pivot flag
Tflag_Reg_j	Register for temporary storage of packet tag
Bypass Queue	Queue of packets which bypass the shaper
<u>Connection Controller i 42 of FIGS. 5 and 6:</u>	
Connection Queue i	Connection i packet queue (Qhead_Reg_i and Qtail_Reg_i contain pointers to head and tail, respectively)
Backlog_Reg_i	Indicates if connection is backlogged
Shaper_Index_Reg_i	Index of rate group to which connection currently belongs
Pivot_Reg_i	Indicates if connection is pivot
<u>Scheduler 68 of FIG. 7:</u>	
Class_Delay_Reg_i	Delay associated with Class i
Timestamp_Reg_i	Timestamp for Class i
<u>Packet:</u>	
tag (in shaper)	Indicates shaping rate of next packet of the connection
tag (in scheduler)	Timestamp by which the packet has to be served

FIGS. **9A–9G** show steps involved in a preferred process according to the current invention. Referring first to FIG. **9A**, following the arrival of packets in step **S510**, one data packet is selected in step **S520**. A connection i and a corresponding delay class c are identified, respectively, in steps **S530** and **S540**. Leaky-bucket computation is performed by leaky-bucket processor **44** of FIG. **5** in step **S550** so as to determine a dominant leaky bucket in step **S560** and a shaping rate g desired by the packet in step **S570**. If, on the other hand, no packet arrives at step **S510**, the process proceeds to step **S750** in FIG. **9C**, which is described below.

Now referring to FIG. **9B**, when the connection is selected by the selector **88** of FIG. **8** in the corresponding delay-class shaper **64** of FIG. **7** or by the selector bypass unit **78** of FIG. **7**, the packet at the head of the connection's queue is to be immediately released to the scheduler **68** of FIG. **7** in step **S580**. If so, it is determined whether or not any connection is backlogged based upon the value in register Backlog_Reg_i **54** of FIG. **6** in step **S590**. Upon confirming a FALSE value, the register Backlog_Reg_j **54** is now set to TRUE in step **S600**, and the number of connections in FIFO_c_g **80** of FIG. **8** of the delay class c and the rate g is examined using the stored value in the register Nconn_Reg_c_g **90** of FIG. **8** in step **S610**. If the number of connections in data packets in step **S740**. If data packets remain, the process goes back to step **S520** to process another data packet. The process proceeds to step **S750** if no new data packets are available.

On the other hand, if the number of connections in the FIFO is zero in step **S610**, the connection i is inserted in the FIFO_c_g **80** in step **S620**. Consequently, the value of the register Nconn_Reg_c_g **90** is incremented by one in step **S630**, and the register Pivot_Reg_i **58** of FIG. **6** is set to TRUE in step **S640**. The value stored in register Timestamp_Reg_c_g **72** of FIG. **7** is incremented in step **S650** by a value L/Rate_Reg_c_g, where L is the packet length and the register Rate_Reg_c_g **92** of FIG. **8** contains the corresponding rate value, and processing proceeds to step **S700**.

Still referring to FIG. **9B**, if the packet is not to be immediately released in step **S580** and the register Backlog_Reg_i **54** of FIG. **6** indicates no backlog in step **S720**, the packet is inserted into the bypass queue **79** of FIG. **7** in step **S730**, and the process proceeds to step **S740**. On the other hand, if the register Backlog_Reg_i **54** indicates some backlog in step **S720**, the packet at the tail of connection queue i **52** of FIG. **6** is marked with TAG g in step **S690**. Step **S690** is also performed after it has been determined that the packet is to be immediately released in step **S580** if the register Backlog_Reg_i **54** in step **S590** indicates some backlog. In either case, after step **S690**, the process proceeds to step **S700**.

Now referring to FIG. **9C**, steps related to the bypass queue **79** in FIG. **7** are illustrated according to the current invention. In step **S750**, it is determined whether or not the selector bypass unit **78** is ready. If it is not ready, the process skips to step **S830**. On the other hand, if the selector bypass unit **78** is ready, a packet at the head of the bypass queue **79** is selected in step **S760**. The connection v is identified in step **S770**, while a corresponding delay class w is identified in step **S780**. After the packet tag is set to the current time Current_Time+Class_Delay_Reg_w in step **S790**, it is determined whether or not the corresponding class queue w **70** of FIG. **7** is empty in step **S800**. If class queue w is empty, the register Timestamp_Reg_w **72** is set to a value contained in the TAG of the data packet in step **S810**, and the process proceeds to step **S820** where the data packet is inserted into class queue w **70**. On the other hand, if class queue w is not empty in step **S800**, the process proceeds directly to step **S820**. Following the insertion, if any selector p **80** of FIG. **8** is ready in step **S830** and any register Nconn_Reg_p_q **90** contains a non-zero value in step **S840**, then the Class_p_Group_y **65** which has a value in register Nconn_Reg_p_y **90** greater than 0 and the smallest value in register Timestamp_Group_Reg_p_y **86** is selected in step **S850**, and the process proceeds to step **S860**. If either or both of the above two conditions as set forth in steps **S830** and **S840** are not met, the process skips to step **S1300**.

Referring to FIG. **9D**, the connection as specified by Class_p_Group_y **64** of FIG. **8** and selected in the above step **S850** is processed as follows. In step **S860**, it is determined whether or not the value stored in the register Timestamp_Group_Reg_p_y **86** is smaller than or equal to the current time Current_Time. If it is not, then the process proceeds to step **S1300**. On the other hand, if the value in the register Timestamp_Group_Reg_p_y **86** is smaller than or equal to the current time Current_Time in step **S860**, a connection j at the top of the queue FIFO_p_y **80** is selected in step **S870**, and the value in the register Pivot_Reg_j **58** of FIG. **6** is stored in the flag register Pflag_Reg_p **104** of FIG. **8** in step **S880**. The corresponding data packet is removed from the connection queue j **52** of FIG. **6** in step **S890**. After the dequeuing, a value in the corresponding TAG is also stored in the flag register Tflag_Reg_p **106** of FIG. **8** in step **S900**. Furthermore, a delay class u for the corresponding connection j is identified in step **S910**, and the TAG of the data packet is set to a value equal to Current_Time+Class_Delay_Reg_u **74** of FIG. **7** in step **S920**. When the class queue u **70** is empty as determined in step **S930**, the register Timestamp_Reg_u **72** is set to the TAG of the data packet in step **S940**. Otherwise, the process proceeds to step **S950**, where the data packet is inserted into class queue u **70**. Lastly, the connection j is removed from the FIFO_p_y **80** of FIG. **8** in step **S960**.

Referring to FIG. **9E**, additional steps are taken to handle a backlog situation. It is determined whether or not the connection j is backlogged in step **S970**. If connection j is not backlogged, then register Backlog_Reg_j **54** of FIG. **6** is set to a FALSE value in step **S980**, the value in register Next_Reg_p_y **102** of FIG. **8** is decremented by one in step **S990**, and processing proceeds to step **S1120**. Upon confirming the backlog in step **S970**, the delay class and rate group corresponding to the register Tflag_Reg_p **106** are used to identify Class_p_Group_z **65** in step **S1000**. If the

rate z is equal to or greater than the group rate y in step **S1010**, the connection j is inserted in FIFO_p_y **80** in step **S1020**, and the process proceeds to step **S1120**.

On the other hand, if the rate z is less than the group rate y in step **S1010**, then the value in register Next_Reg_p_y **102** is decremented by one in step **S1030**. If it is determined in step **S1040** that the register Nconn_Reg_p_z **90** stores a zero value, the connection j is inserted into FIFO_p_z **80** in step **S1050** and the value in register Nconn_Reg_p_z **90** is incremented by one in step **S1060**. Subsequently, the register Pivot_Reg_j **58** of FIG. **6** is set to a TRUE value in step **S1070**, while the value in register Timestamp_Group_Reg_p_z **86** is incremented by (L/Rate_Reg_p_z), where L is the packet length, in step **S1080**, and processing proceeds to step **S1120**.

On the other hand, in step **S1040**, if the register Nconn_Reg_p_z **90** does not contain a zero value, the register Pivot_Reg_j **58** of FIG. **6** is set to a FALSE value in step **S1090**, and the connection j is inserted into Insertq_p_z **94** in step **S1100**. Lastly, the value in register Ninserts_Reg_p_z **100** is incremented by one in step **S1110**.

If the register Pflag_Reg_p **104** contains a TRUE value in step **S1 120**, the process proceeds to step **S1130**. On the other hand, if the register Pflag_Reg_p **104** does not contain a TRUE value, then the register Timestamp_Group_Reg_p_y **86** is incremented by (L/Nconn_Reg_p_{13} y*Rate_Reg_p_y) in step **S1290**, and the process proceeds to step **S1300**.

Now referring to FIG. **9F**, steps related to the register Next_Reg_p_y **102** of FIG. **8** are handled. If the value in register Next_Reg_p_y **102** is not zero in step **S1130**, a connection m at the tail of FIFO_p_y **80** is identified in step **S1220**, and the value in the corresponding register Pivot_Reg_m **58** of FIG. **6** is set to TRUE in step **S1230**. Insertq_p_y **94** of FIG. **8** is appended to the tail of FIFO_p_y **80** in step **S1240**, while the register Nconn_Reg_p_y **90** is set to the value in register Next_Reg_p_y **102** in step **S1250**. The value in register Next_Reg_p_y **102** is incremented by the value in register Ninserts_Reg_p_**100** in step **S1260**, and the register Ninserts_Reg_p_y **100** is reset to zero in step **S1270**. Lastly, the value in register Timestamp_Group_Reg_p_y **86** is incremented by (L/Nconn_Reg_p_{y*Rate}_Reg_p_y) in step **S1280**, and the process proceeds to step **S1300**.

On the other hand, if the value in register Next_Reg_p_y **102** is zero in step **S1130**, Insertq_p_y **94** is appended to the tail of FIFO_p_y **80** in step **S1140**, while the value in register Nconn_Reg_p_y **90** is set to the value in register Ninserts_Reg_p_y **100** in step **S1150**, the value in register Next_Reg_p_y **102** is set to the value in register Ninserts_Reg_p_y **100** in step **S1160**, and the register Ninserts_Reg_p_y **100** is reset to zero in step **S1170**. Subsequently, it is determined in step **S1180** whether or not the value in register Nconn_Reg_p_y **90** is larger than zero. If not, the process proceeds to step **S1300**. On the other hand, if the value in register Nconn_Reg_p_y **90** is larger than zero, a connection k at the head of FIFO_p_y **90** is identified in step **S1190**, and the corresponding register Pivot_Reg_k **58** of FIG. **6** is set to TRUE in step **S1200**. Lastly, the value in register Timestamp_Group_Reg_p_y **86** of FIG. **8** is incremented by (L/Rate_Reg_p_y) in step **S1210** before proceeding to step **S1300**.

Referring to FIG. **9G**, a data packet is sent via transmitter **50** of FIG. **5** in the following steps. In step **S1300**, it is determined whether or not transmitter **50** is available. If it is not available, the process returns to step **S510**. On the other hand, if the transmitter is available in step **S1300**, the nonempty class queue b **70** of FIG. **7** with the smallest value in the corresponding register Timestamp_Reg_b **72** is selected in step **S1310**. The data packet at the head of the selected class queue b **70** is sent to transmitter **50** in step **S1320**. After sending the data packet, it is determined whether or not class queue b **70** is empty in step **S1330**. If it is already empty, the process returns to step **S510**. In case the queue is not yet empty, the value in register Timestamp_Reg_b **72** is set to the TAG value of the data packet at the head of class queue b **70** in step **S1340** before returning to step **S510**.

In summary, a tag associated with the packet is used to determine whether or not the connection is to be jumped to a FIFO corresponding to a lower rate group. If so, it is inserted into the insertion queue corresponding to the new rate group. The insertion queue is appended to the FIFO corresponding to the new rate group only when the pivot corresponding to the new rate group has been selected by selector **88** of FIG. **8**. If, on the other hand, the tag indicates that a rate jump is not required, and the connection is still backlogged, it is reinserted at the tail of the same FIFO. The scheduler **68** of FIG. **7** maintains a class queue **70** of packets for every delay class. Scheduling is only performed among packets at the head of the class queues **70**. If connection i belongs to a particular delay class j, then every time a packet belonging to connection i enters the scheduler **68** (from the shaper **63** or via the selector bypass unit **78**), it is assigned a timestamp ahead of the current time by the delay value associated with that delay class, and linked at the tail of the corresponding class queue j **70**. Each delay queue is served in a first-in-first-out manner since all packets in the queue have identical delay constraints. At each decision instant, the scheduler **68** selects the packet with the minimum timestamp among the packets at the head of each class queue **70**. This timestamp value is stored in the corresponding register Timestamp_Reg **72**, and the sorting of the C timestamps is accomplished by the sorter **76** within the scheduler **68**.

FIG. **10** shows in flowchart form the computation of the delay incurred by an incoming packet in leaky bucket k. The leaky buckets together define the envelope on the connection's traffic. Registers Sigma_k and Rho_k hold the token bucket size and release rate, respectively, for the leaky bucket, while register Last_Release_k denotes the release time for the last packet and register Token_Counter_k denotes the current token count. In step **S2010**, it is determined whether or not the current time Cur_Time is larger than the value in register Last_Release_k. If it is not true, the process proceeds to step **S2040**. Otherwise, in step **S2020**, the value in register Token_Counter_k is determined, and, in step **S2030**, the register Last_Release_k is updated to the current time. Subsequently, in step **S2040**, the register Last_Release_k is incremented by MAX (**0**, (L-Token_Counter)/Rho_k). After the register Token_Counter_k is set to MAX (**0**, Token_Counter_k-L) in step **S2050**, the delay incurred by the packet is returned in the register Delay_k in step **S2060**. The overall delay incurred by the packet in the system of multiple leaky buckets (which together describe the envelope for the connection) is obtained as the maximum of the delays incurred in the individual leaky buckets, and this maximizing leaky bucket also determines the shaping rate and hence the rate group associated with the packet.

In the above, although the operation of the shaper has been described in the context of the implementation of an RC-EDF server, similar principles may be used in the implementation of shapers for other scheduling disciplines, wherein the shaping rates supported by the shaper are a

discrete number, such as the disciplines described in F. M. Chiussi, A. Francini and J. G. Kneuer, "Implementing Fair Queueing in ATM Switches—Part 2: The Logarithmic Calendar Queue," *Proc. GLOBECOM'97*, pp. 519–525, November 1997; J. C. R. Bennett, D. C. Stephens and H. Zhang, "High Speed, Scalable, and Accurate Implementation of Fair Queueing Algorithms in ATM Networks," *Proc. ICNP'97*, pp. 7–14, October 1997.

In accordance with another aspect of the invention, the embodiments are identical to the first aspect described above except that rate jumps are handled differently. To be more specific, rate jumps are still performed only from a higher rate to a lower rate. However, if a packet for a connection arrives at the server while the connection is still backlogged and requests a shaping rate that is higher than the shaping rate requested by the previous packet for that connection, the connection is treated as newly backlogged and immediately queued into the FIFO corresponding to the new rate group. This implies that, at any given time, a connection may be waiting in more than one FIFO.

This aspect of the invention requires some modifications in the embodiments of the first aspect of the invention. Within each connection controller **42** of FIG. **5**, the register Shaper_Index_Reg **56** of FIG. **6** is replaced by a link list of virtual connections. Each element of this link list corresponds to an entry in the FIFOs corresponding to the rate groups, and holds the index of the rate group with which it is associated. Further, FIFO_j_i **80** of FIG. **8** can contain virtual connection entries in it. This structure enables a connection to be in multiple FIFOs at the same time by replicating into various virtual connections. The arrangement, though not explicitly described here, can nevertheless easily be devised from the principles stated above.

In one embodiment, the present invention is a system which services a plurality of queues associated with respective data connections in a packet communication network such that the system guarantees data transfer delays between the data source and the destination of the data connections. This is achieved in two stages: the first stage shapes the traffic of each connection such that it conforms to a pre-specified envelope, while the second stage associates timestamps with the packets released by the first stage and chooses for transmission from among them the one with the smallest timestamp. Both stages are associated with a discrete set of delays classes. The first stage employs one shaping structure per delay class. Each shaping structure in turn supports a discrete set of rates and employs a FIFO of connections per supported rate. A connection may move between FIFOs corresponding to different rates as its rate requirement changes. The second stage associates with each packet exiting the first stage a timestamp given by the exit time from the first stage and the delay class to which the connection belongs. A queue of packets is maintained per delay class, and the scheduler selects for transmission from among the packets at the head of the queues the one with the smallest timestamp.

In at least one embodiment, the present invention is a method for shaping the data traffic of a plurality of connections, the connections traversing an associated communication switch, each of the connections being associated with a respective set of shaping rates and a respective data transfer delay time, each of the shaping rates being one of a first predetermined number of supported shaping rates, and each of the data transfer delay times being one of a second predetermined number of supported delay time classes, each of the connections being further associated with respective queues containing data packets. The method comprises the steps of:

(1) identifying for each data packet received via a plurality of data links, the respective one of the connections and the associated one of the queues;

(2) storing each of the received data packets in the identified queue;

(3) computing for each of the received data packets the respective one of the shaping rates, and associating the computed shaping rate with the data packet;

(4) identifying for each of the received data packets the respective one of the delay time classes;

(5) associating a queue of connections with each connection wherein the associated queue of data packets has at least one data packet waiting therein, the queue of connections being associated with one of the supported delay time classes and one of the supported shaping rates, the queue of connections being associated with the delay time class and shaping rate associated with the packet at the head of the queue of data packets associated with the connection;

(6) associating a first timestamp with each queue of connections, including generating a new first timestamp each time a connection enters an empty queue of connections, wherein a system time is used in the generation of the new first timestamp;

(7) associating a cumulative service rate with each of the queues of connections, the cumulative service rate being used to generate the respective first timestamp associated with each of the queues of connections;

(8) selecting one of the first timestamps associated with the queues of connections associated with each delay time class which have at least one connection waiting for service therein, and identifying the connections at the head of the queue of connections associated with the selected first timestamps as the recipient of the next service, the service including the steps of removing a data packet from the head of the queue associated with the identified connections, and transmitting the data packets;

(9) determining if the queue of data packets associated with the serviced connection has data packets waiting therein, and storing the connection in the queue of connections associated with the delay time class and shaping rate associated with the packet at the head of the queue of data packets;

(10) determining if the queue of connections associated with the serviced connection has connections waiting therein, and computing a new first timestamp associated to the queue of connections using the associated cumulative service rate.

In at least one embodiment, the set of shaping rates associated with each of the connections identifies an associated traffic envelope.

In at least one embodiment, the shaping rates respectively correspond to a slope value corresponding to a piece of a piecewise linear envelope.

In at least one embodiment, the selected data packets are transmitted to an output.

In at least one embodiment, the queues of connections are first-in-first-out link lists.

In at least one embodiment, the cumulative service rate associated with each of the queues of connections is equal to the number of connections in that queue times the shaping rate corresponding to that queue.

In at least one embodiment, the cumulative service rate associated with each of the queues of connections is updated when a connection identified as pivot connection is served, the pivot connection being one of the connections in the queue of connections.

In at least one embodiment, the new first timestamp computed when a queue of connections is served and having data packets waiting therein is equal to the previous timestamp incremented by the length of the data packet at the head of the queue of data packets associated with the connection at the head of the queue of connections, divided by the cumulative service rate.

In at least one embodiment, a connection stored in a previously empty queue of connections is identified as the pivot connection.

In at least one embodiment, the connection stored after the pivot connection in the associated queue of connections at the time when the pivot connection is served and is not stored back in the queue of connection is declared as the new pivot connection.

In at least one embodiment, the invention further comprises a method of guaranteeing a delay time to each connection, said method comprising the steps of:

(a) associating a queue of data packets with each of the supported delay time classes;

(b) associating each served packet with a second timestamp equal to the system time plus the delay time associated with the corresponding connection, removing the packet from the queue of packets associated with the connection and storing the removed data packet to the tail of the queue of data packets associated with the delay time class; and

(c) selecting one of the second timestamps associated with the data packets at the head of the queues associated with the delay time classes which have at least one packet waiting therein as the recipient of the next service, the service including the steps of removing the data packet from the head of the queue associated with the delay bound class of the selected timestamp, and transmitting the removed data packet to an output.

In at least one embodiment, the selected second timestamp is the minimum of the timestamp associated with the data packets at the head of the queues associated with the delay time classes which have at least one packet waiting therein.

The illustrative embodiments described above are but two examples of the principles that may be used to schedule the transmission of data packets according to the present invention. Those skilled in the art will be able to devise numerous arrangements, which, although not explicitly shown or described herein, nevertheless embody those principles that are within the spirit and scope of the present invention.

What is claimed is:

1. A method of shaping data traffic of one or more connections traversing a: switch, the method comprising the steps of:

a) determining a shaping rate and a transfer delay class for one or more data packets of a connection received at the switch;

b) enqueueing (i) each data packet of the connection in a data queue associated with one or more connections having the same shaping rate and transfer delay class as the data packet and(ii) the connection in a corresponding connection queue associated with one or more connections having the same shaping rate and transfer delay class as the data packet;

c) selecting for service, for a transfer delay class, a connection in a non-empty connection queue having the corresponding transfer delay class, based on a timestamp of the connection queue;

d) transmitting one or more data packets of the selected connection from the corresponding data queue;

e) dequeueing the selected connection from the connection queue; and

f) enqueuing the dequeued connection back into the connection queue, if the dequeued connection has one or more remaining data packets in the corresponding data queue.

2. The method as recited in claim **1**, further comprising the step of g) updating a cumulative service rate and a timestamp of the connection queue of the enqueued selected connection, wherein

the timestamp for the connection queue is determined from the cumulative service rate of the queue and a system potential of the switch when a connection is enqueued in a corresponding connection queue that is empty.

3. The method as recited in claim **2**, wherein, for step g), the cumulative service rate is updated for each service of a pivot connection enqueued in a corresponding connection queue.

4. The method as recited in claim **2**, wherein, for step g), the cumulative service rate of the queue is related to a combination of i) a number of connections in the connection queue and ii) the corresponding shaping rate of the connection queue.

5. The method as recited in claim **2**, wherein, for step g), the timestamp is updated when the connection queue is served and remains un-empty, and the updated timestamp is computed as i) the timestamp that is incremented by a length of the data packet at the head of the data queue associated with the connection at the head of the corresponding connection queue that is served, which incremented timestamp is then divided by the cumulative service rate.

6. The method as recited in claim **5**, wherein a connection enqueued in a empty connection queue is a pivot connection, and a connection stored after the pivot connection is set as a new pivot connection if the pivot connection is dequeued and not enqueued after the pivot connection is served in step c).

7. The method as recited in claim **1**, wherein, for step a), each shaping rate corresponds to a traffic envelope associated with data packets of a connection.

8. The method as recited in claim **1**, wherein, for step a), each shaping rate corresponds to a value of slope for a segment of a piece-wise linear traffic envelope.

9. The method as recited in claim 1, wherein, for steps b) through f), each connection queue is a first-in, first-out linked list.

10. The method as recited in claim 1, further comprising the step of g) guaranteeing a delay time to each connection, step g) comprising the steps of:

g1) associating a data queue with each delay class, each data queue having data packets of a corresponding connection with the determined transfer delay class of step a);

g2) associating a second timestamp for each data queue for data packets of the connection serviced with steps c) and d) Wherein the second timestamp is set as a combination of the system potential and the delay time of the delay class associated with the serviced data packet;

g3) dequeuing the serviced data packet from the corresponding connection queue;

g4) enqueuing the service data packet at the tail of the data queue with the delay class equivalent to the delay class of the corresponding connection queue;

g5) selecting a data packet from one of the data queues based on the second timestamp; and

g7) transmitting the selected data packet.

11. The method as recited in claim **10**, wherein the selected second timestamp is a relative minimum timestamp of the non-empty connection queues, wherein each non-empty connection queue is a connection queue associated with the data packets at the head of the data queues.

12. Apparatus for shaping data traffic of one or more connections traversing a switch, the apparatus comprising:.

a shaper determining a shaping rate and a transfer delay class for one or more data packets of a connection received at the switch; and

a server enqueueing (i) each data packet of the connection in a data queue associated with one or more connections having the same shaping rate and transfer delay class as the data packet and (ii) the connection in a corresponding connection queue associated with one or more connections having the same shaping rate and transfer delay class as the data packet,

wherein the server i) selects for service, for a transfer delay class, a connection in a non-empty connection queue having the corresponding transfer delay class, based on a timestamp of the connection queue, and ii) causes one or more data packets of the selected connection to be transmitted from the corresponding data queue; and

wherein the server 1) dequeues the selected connection from the connection queue; and 2) enqueues the dequeued connection back into the connection queue, if the dequeued connection has one or more remaining data packets in the corresponding data queue.

13. The apparatus as recited in claim **12**, wherein the shaper updates a cumulative service rate and a timestamp of the connection queue of the enqueued selected connection, the timestamp for the connection queue determined from the cumulative service rate of the queue and a system potential of the switch when a connection is enqueued in a corresponding connection queue that is empty.

14. The apparatus as recited in claim **12**, wherein the apparatus is embodied in either a switch or a router of a packet network.

15. A computer-readable medium having stored thereon a plurality of instructions, the plurality of instructions including instructions which, when executed by a processor, cause the processor to implement a method for shaping data traffic of one or more connections traversing a switch, the method comprising the steps of:

a) determining a shaping rate and a transfer delay class for one or more data packets of a connection received at the switch;

b) enqueueing (i) each data packet of the connection in a data queue associated with one or more connections having the same shaping rate and transfer delay class as the data packet and (ii) the connection in a corresponding connection queue associated with one or more connections having the same shaping rate and transfer delay class as the data packet;

c) selecting for service, for a transfer delay class, a connection in a non-empty connection queue having the corresponding transfer delay class, based on a timestamp of the connection queue;

d) transmitting one or more data packets of the selected connection from the corresponding data queue;

e) dequeueing the selected connection from the connection queue; and

f) enqueuing the dequeued connection back into the connection queue, if the dequeued connection has one or more remaining data packets in the corresponding data queue.

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